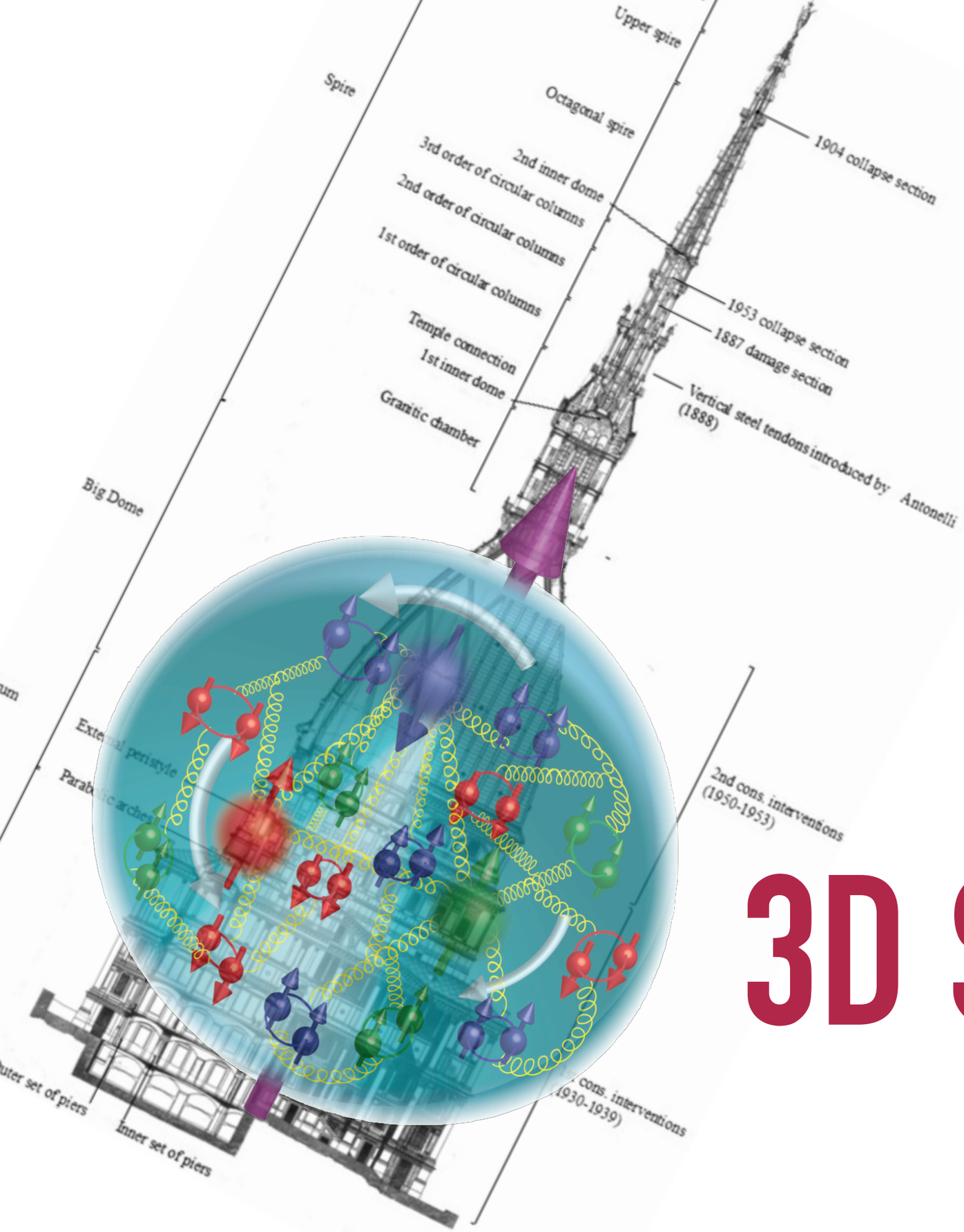


SPIN AND 3D STRUCTURE

Alessandro Bacchetta
and Alexei Prokudin

AP funding agencies:

NSF

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

TMD Collaboration

Jefferson Lab

PennState Berks

AB funding agencies:

3DSPIN
MAPPING THE PROTON IN 3D

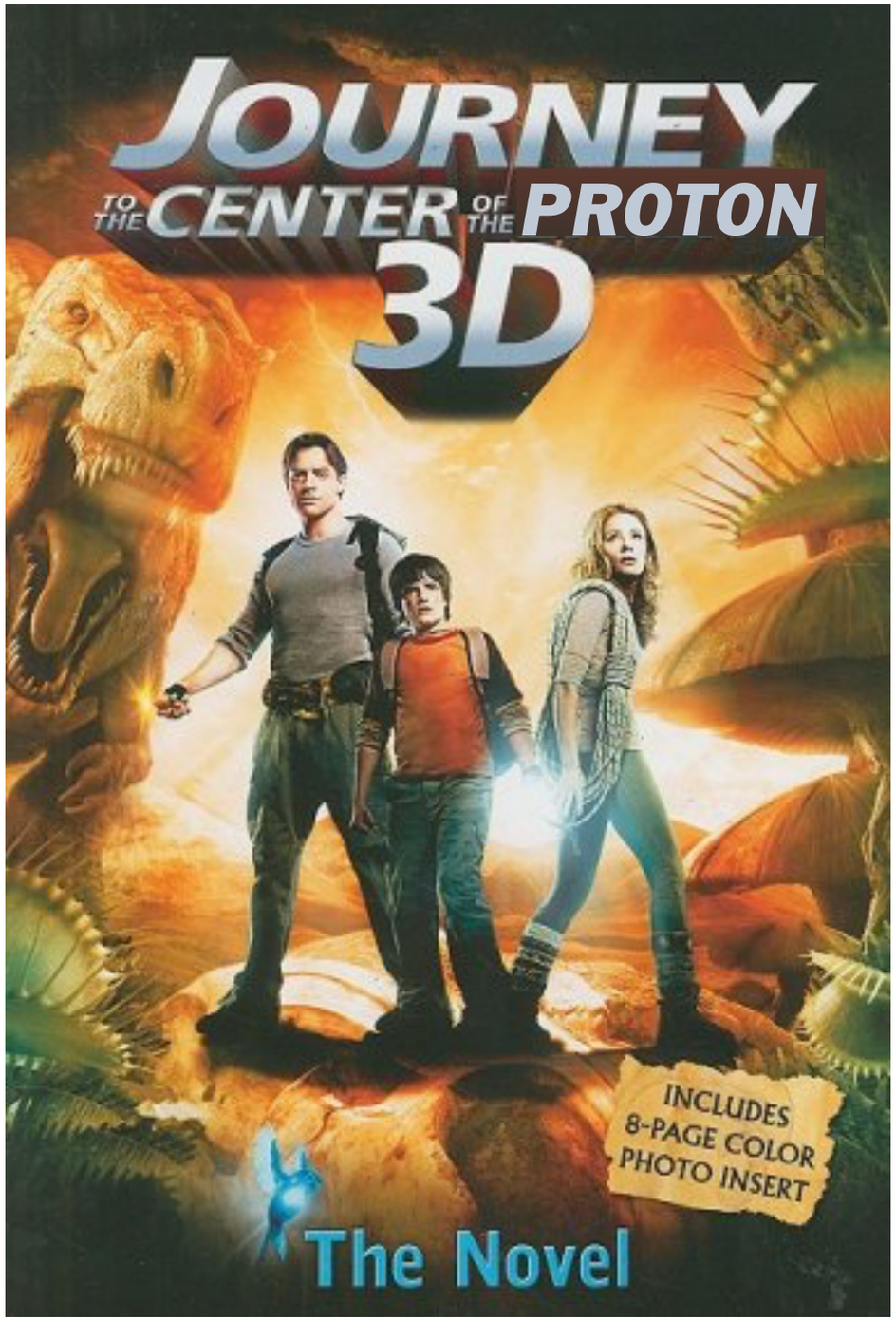
erc
European Research Council

INFN
Istituto Nazionale di Fisica Nucleare

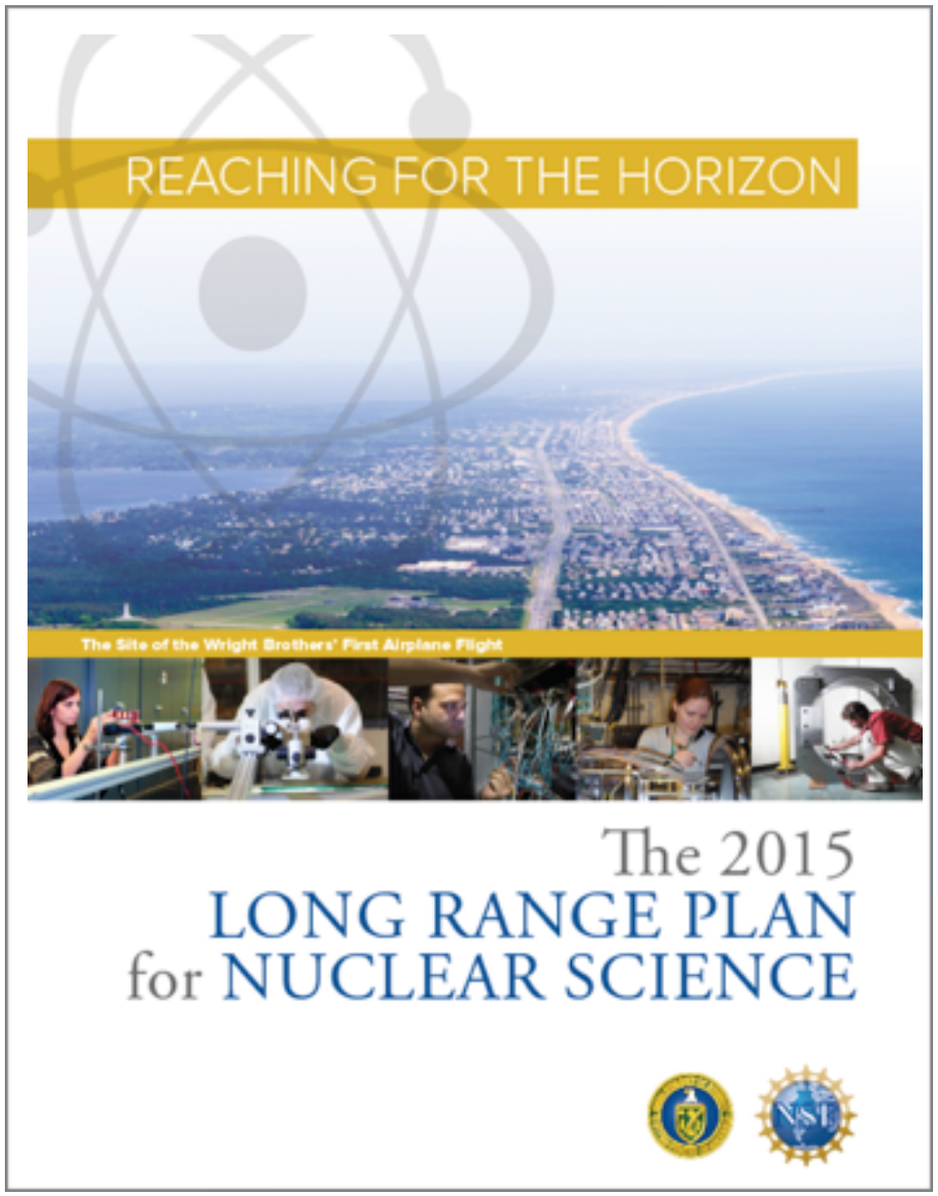
UNIVERSITÀ DI PAVIA

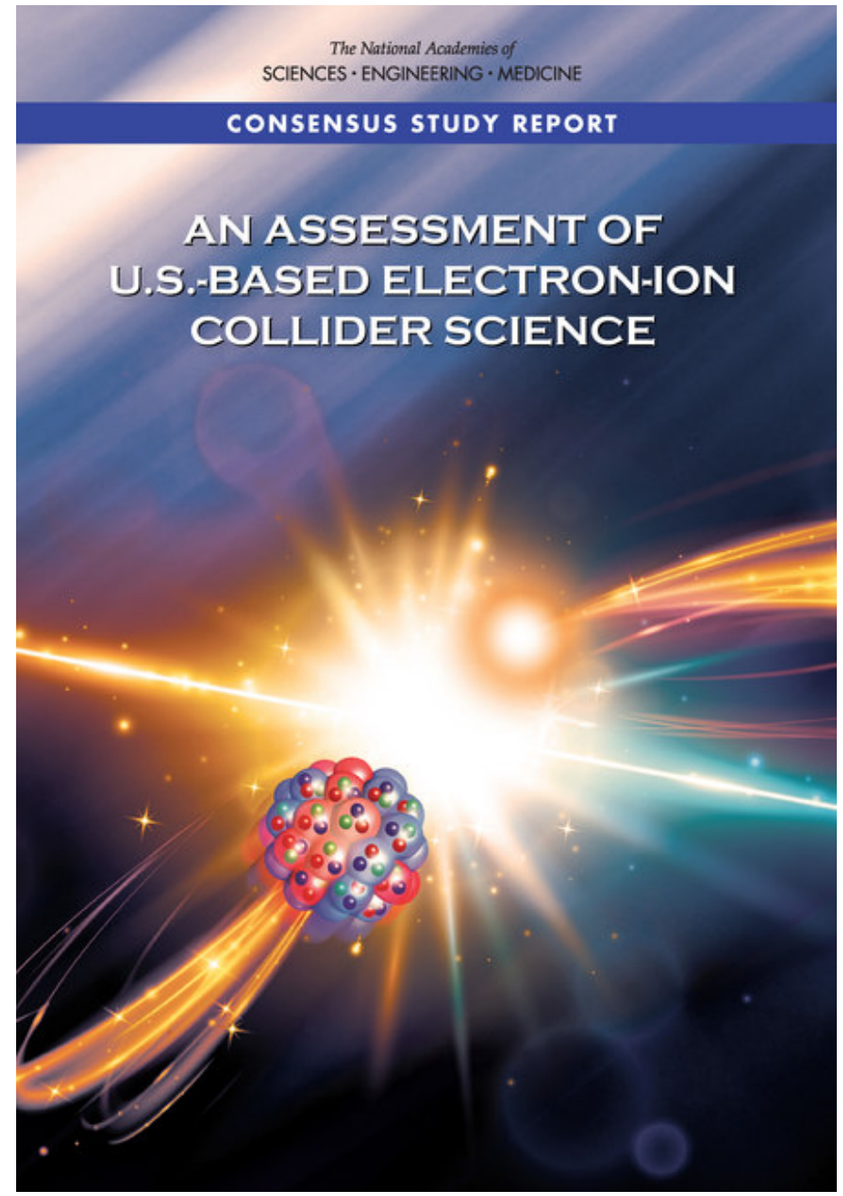
Not only a world-expert in spin and 3D structure,
but also post-doc in Torino
from 2001 to 2009

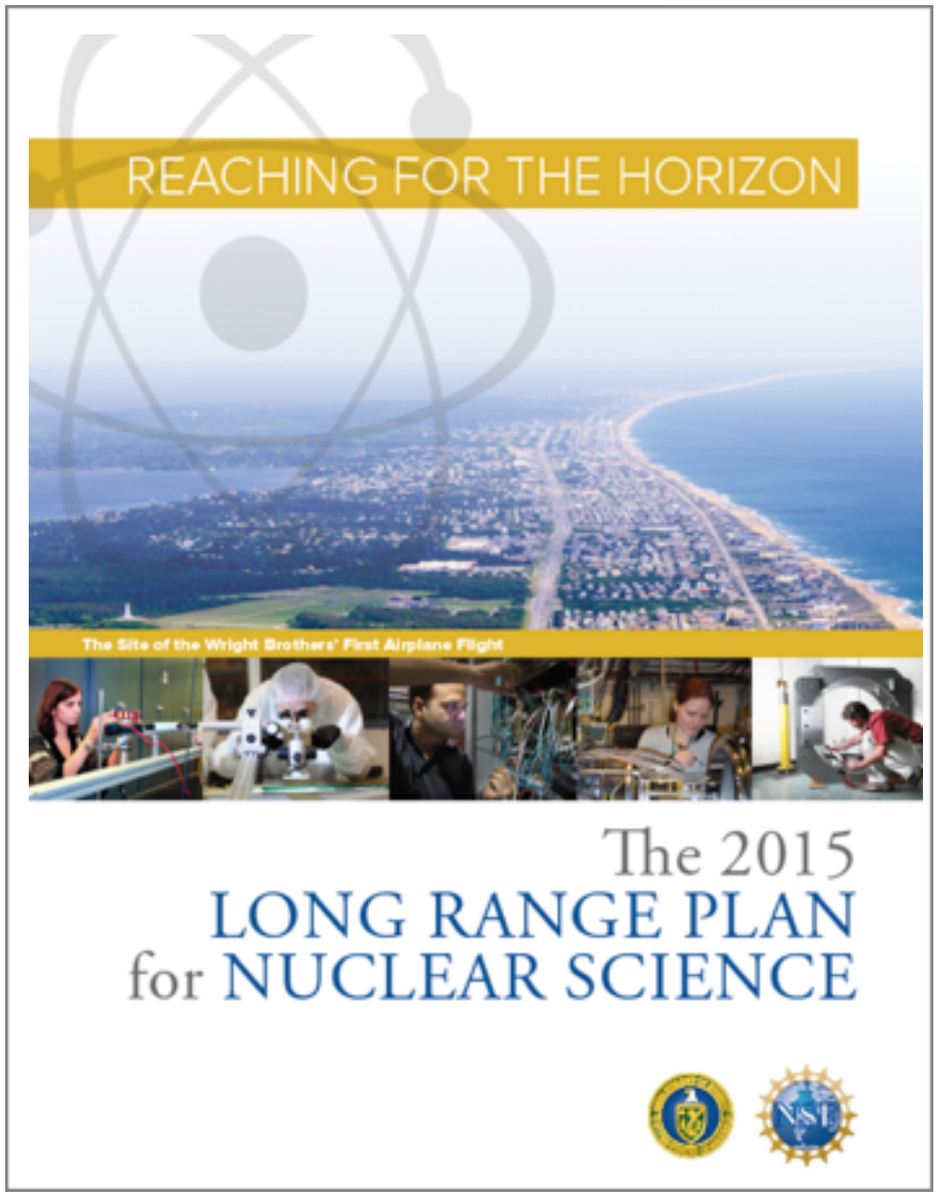
RELEVANT LITERATURE



RELEVANT LITERATURE (SERIOUSLY)







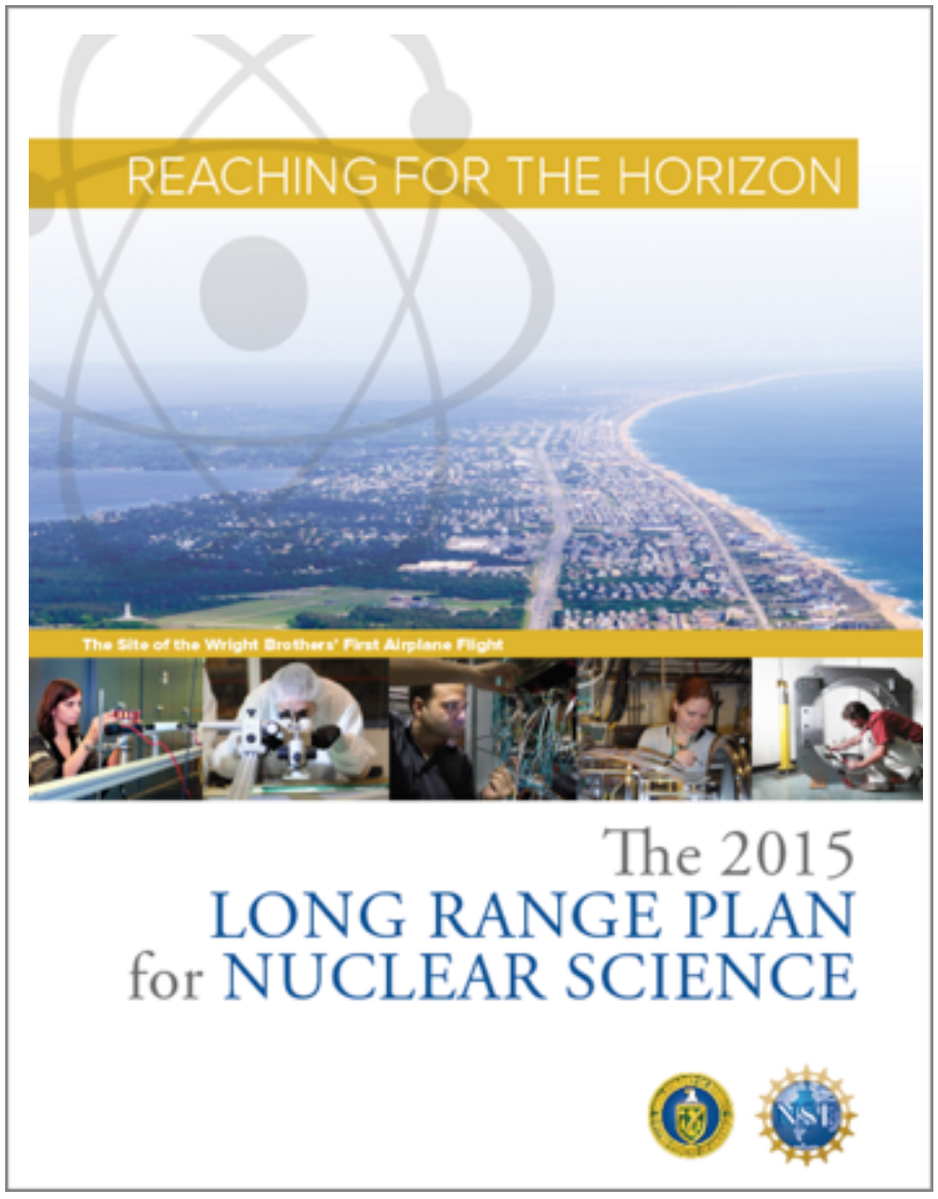
RECOMMENDATION I

...

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*

...

- *The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.*

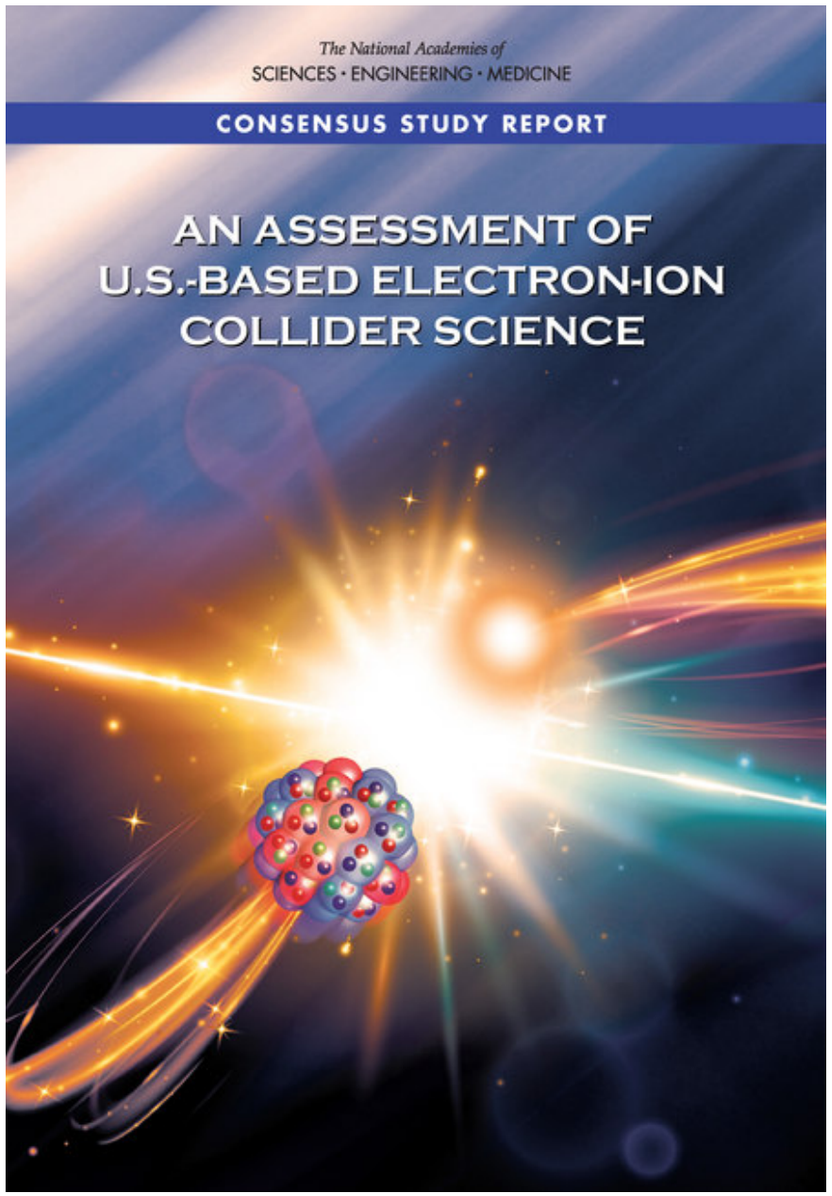


RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier

...



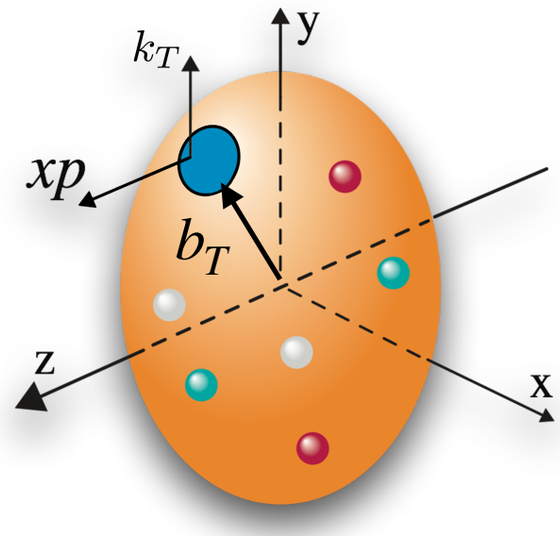
Finding 1: An EIC can uniquely address three profound questions about nucleons —neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

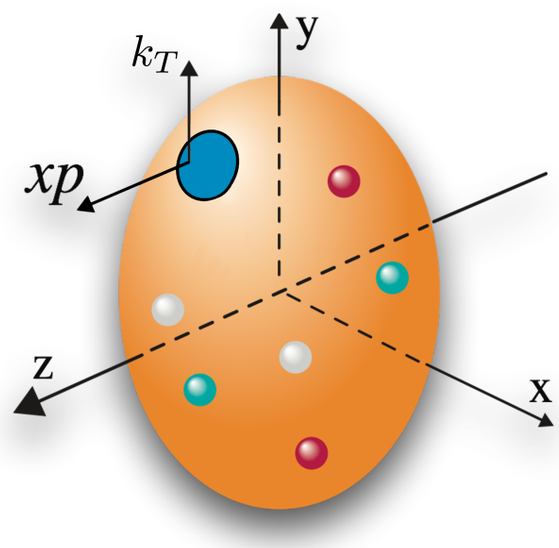
The field of “spin and 3D structure” is prominently included in the strategic plans of the US

We hope that the EU will give an equally strategic support!

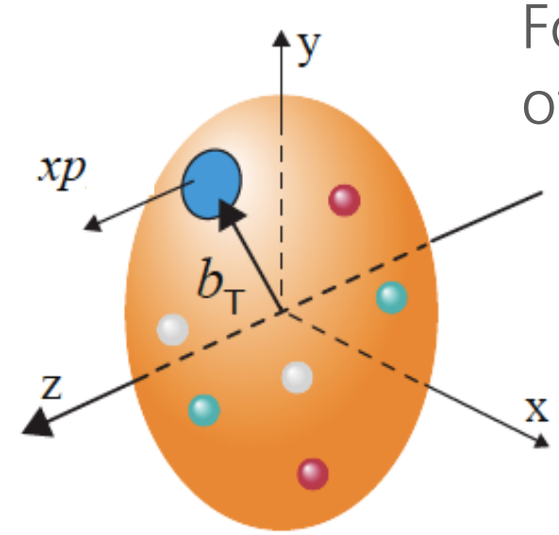
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)



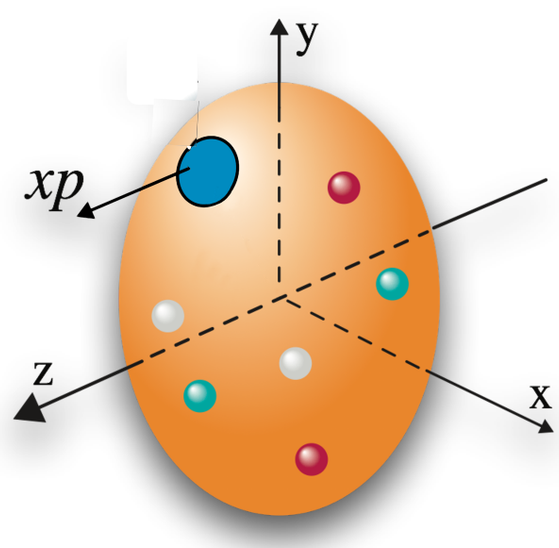
TMDs



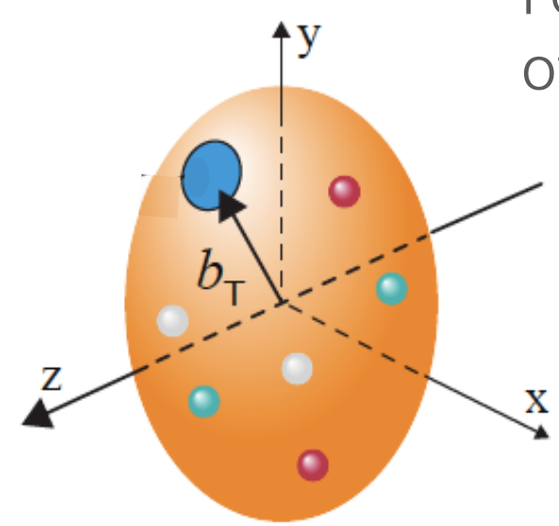
Fourier transform of GPDs



PDFs



Fourier transform of Form Factors



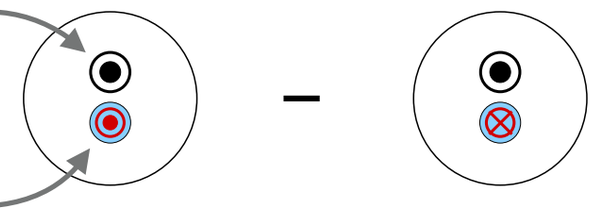
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

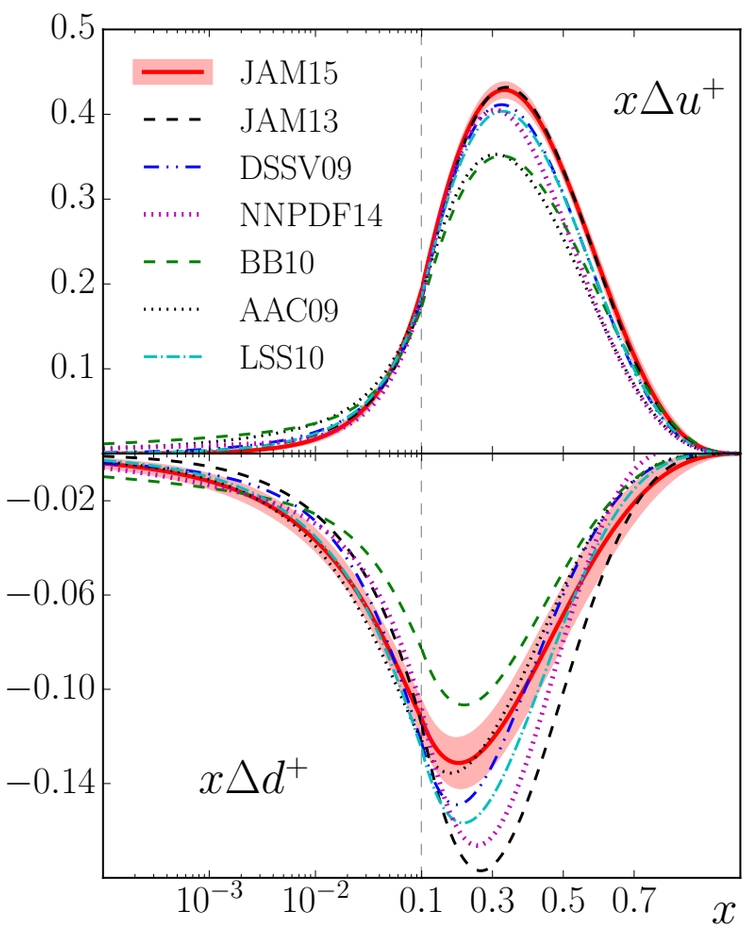
SPIN

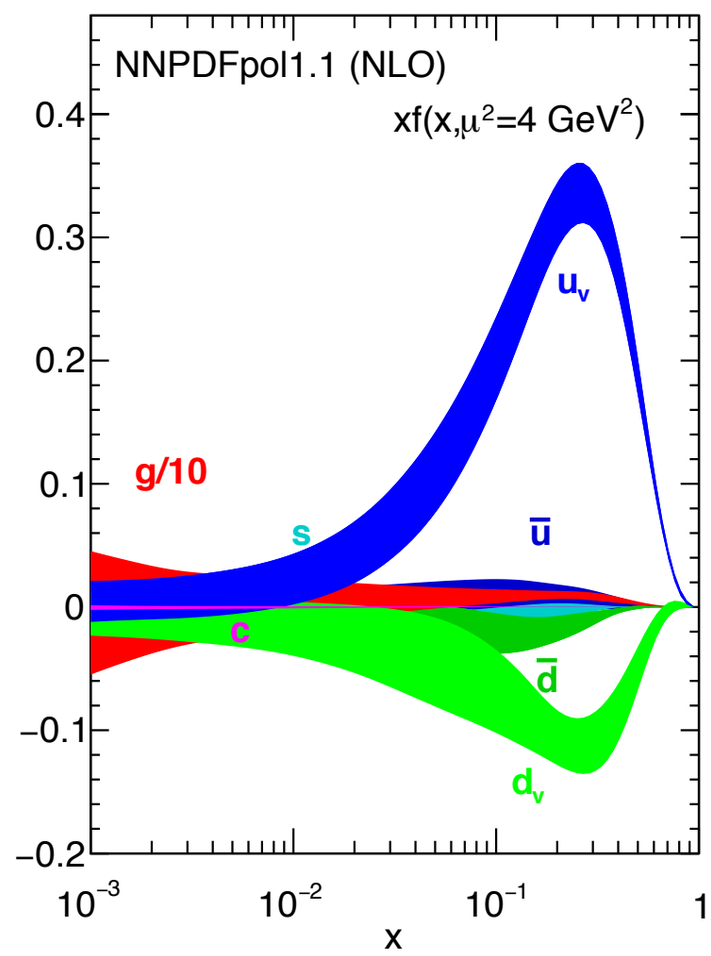
HELICITY PARTON DISTRIBUTION FUNCTIONS

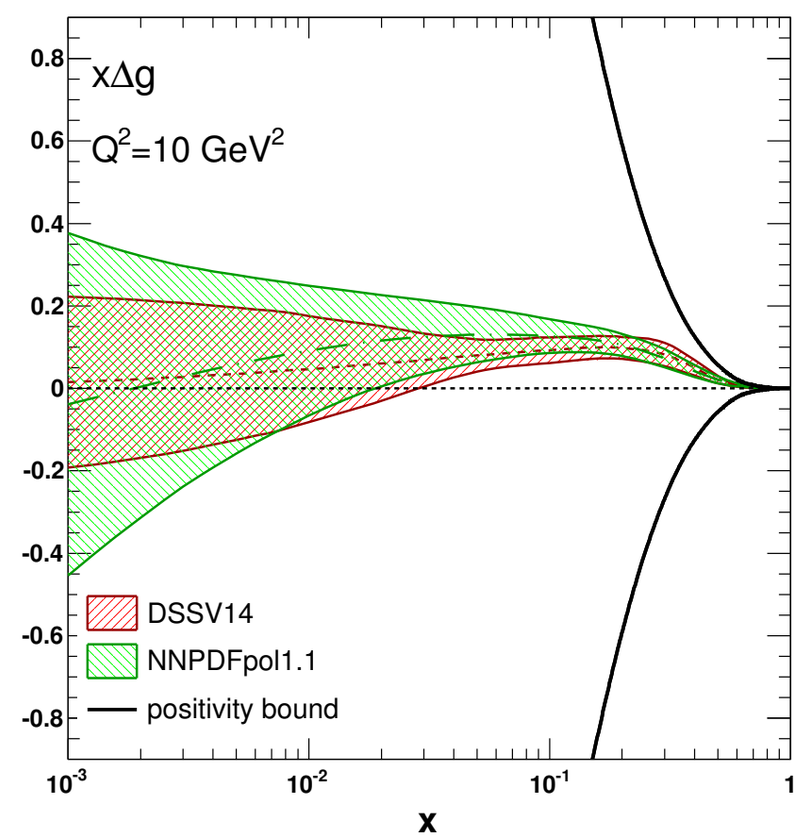
longitudinally polarized target

longitudinally polarized quark





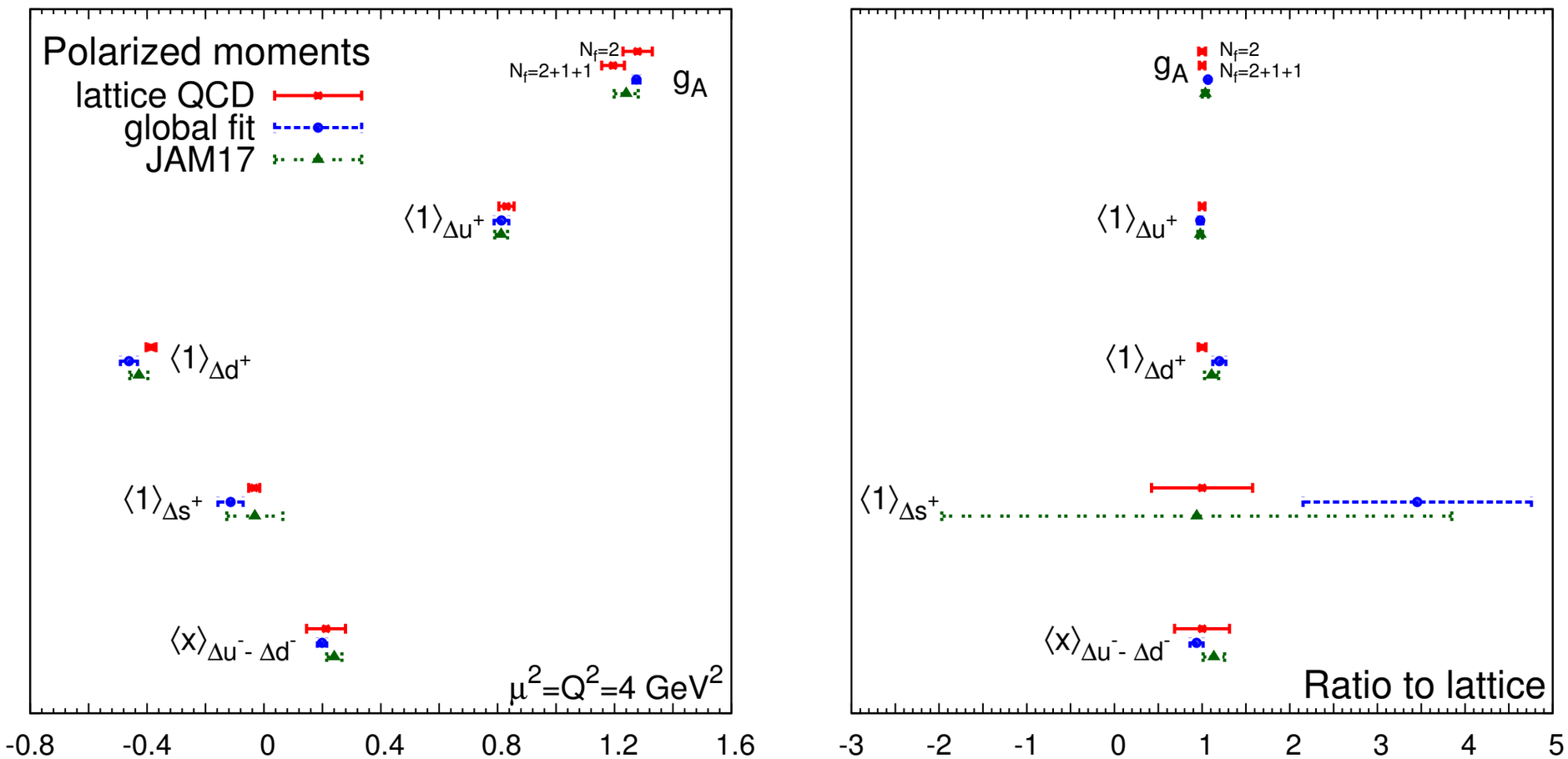




Sato et al., arXiv:1601.07782

arXiv:1711.07916

COMPARISON WITH LATTICE

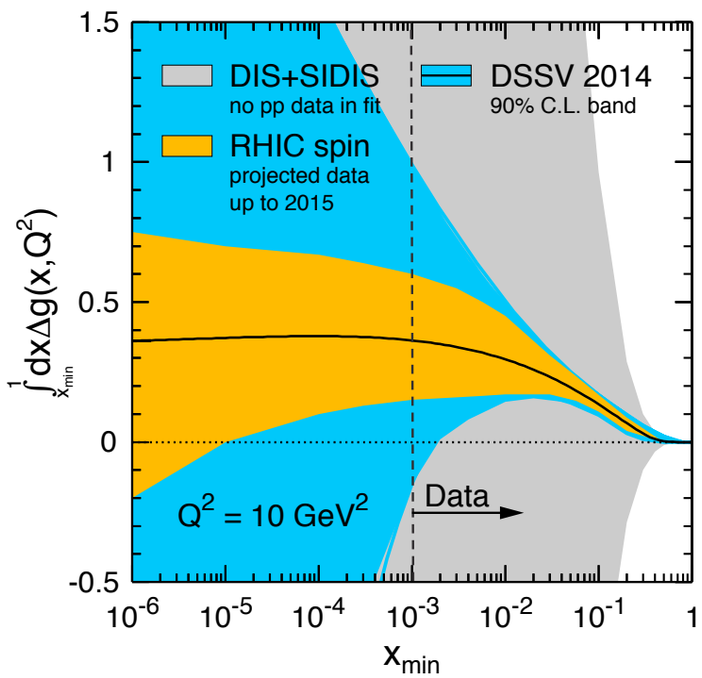


PDFlattice document, arXiv:1711.07916

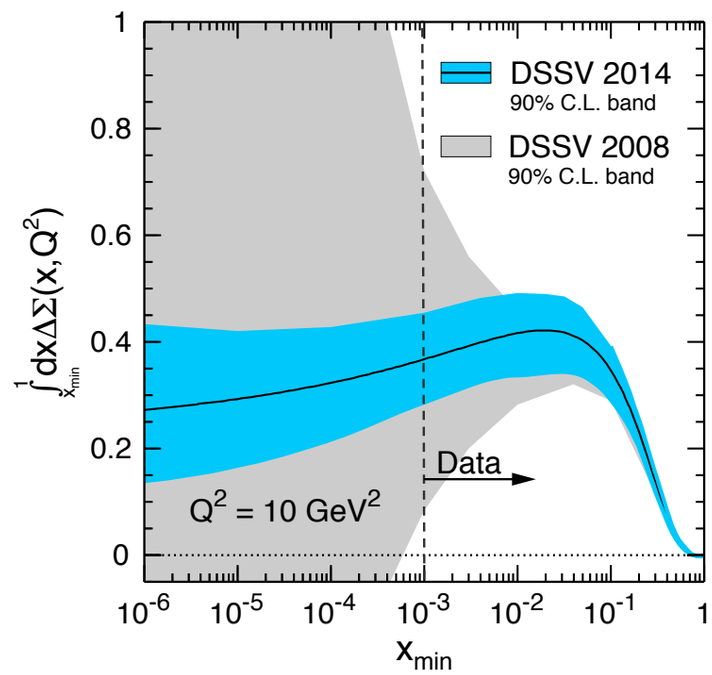
Remarkable agreement between extracted moments of helicity distributions and lattice QCD calculations

PARTON'S CONTRIBUTIONS TO ANGULAR MOMENTUM

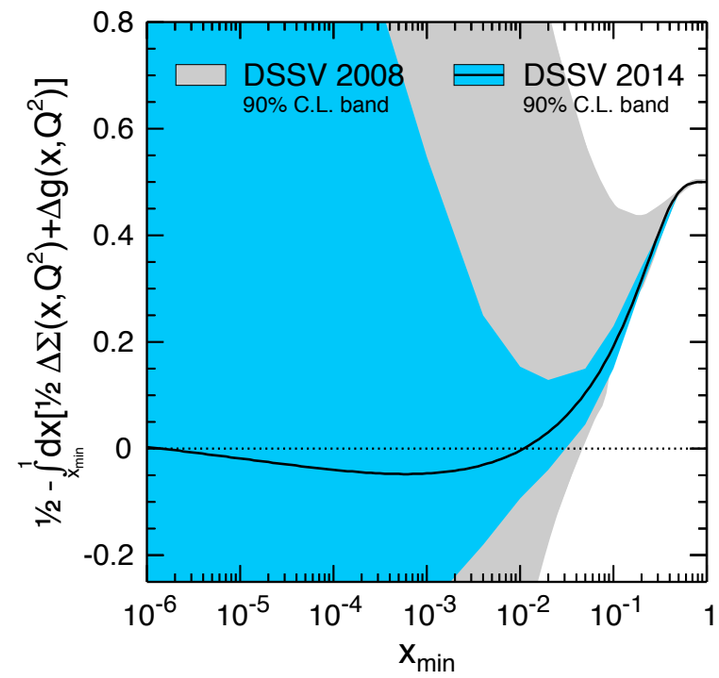
gluon spin

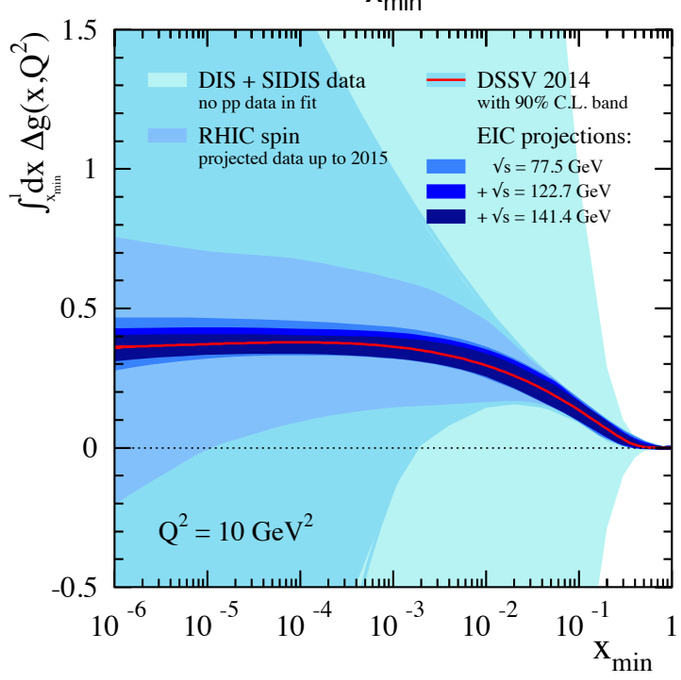


quark spin



orbital
angular momentum



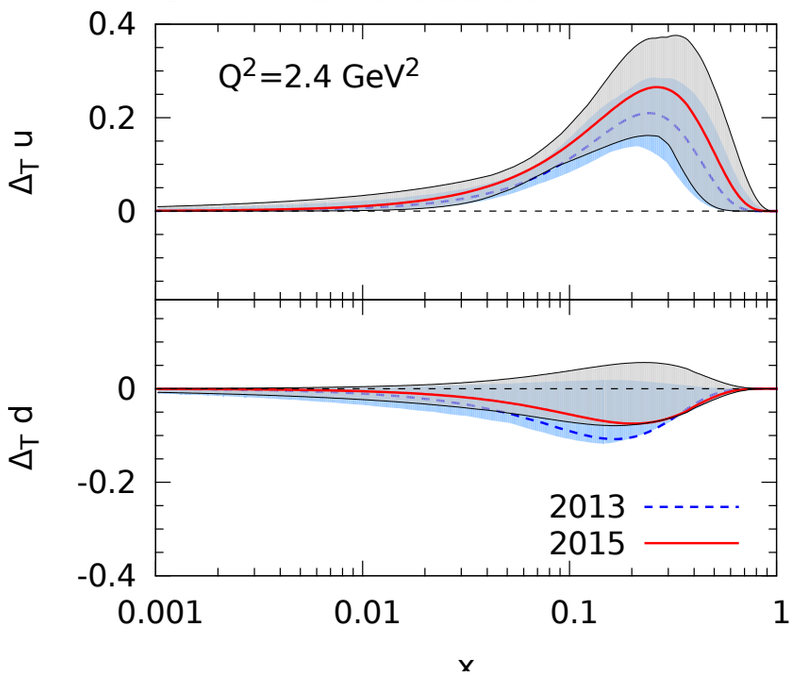


Aschenauer et al., arXiv:1708.01527 and arXiv:1509.06489

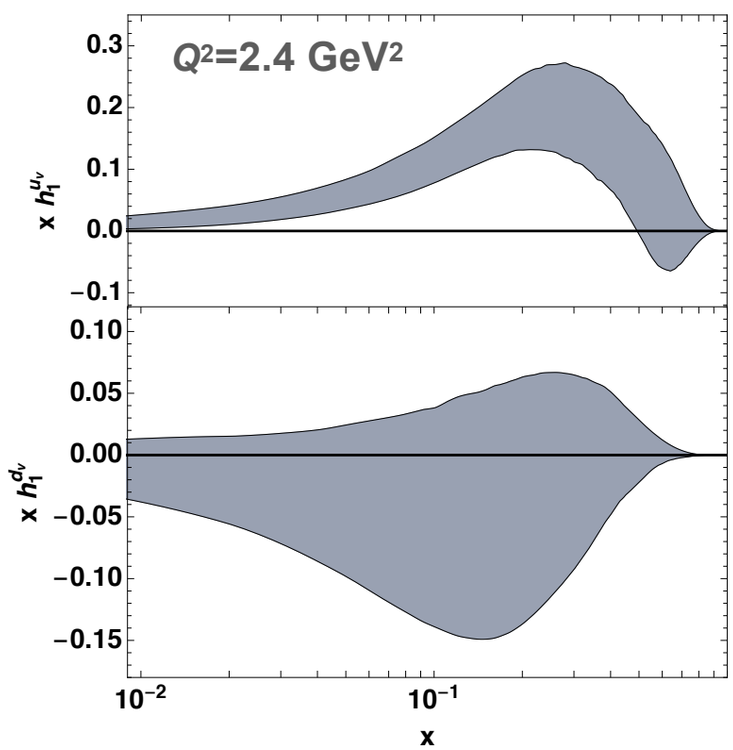
We are constantly improving the knowledge of the contributions to the spin of the proton

TRANSVERSITY PARTON DISTRIBUTION FUNCTION

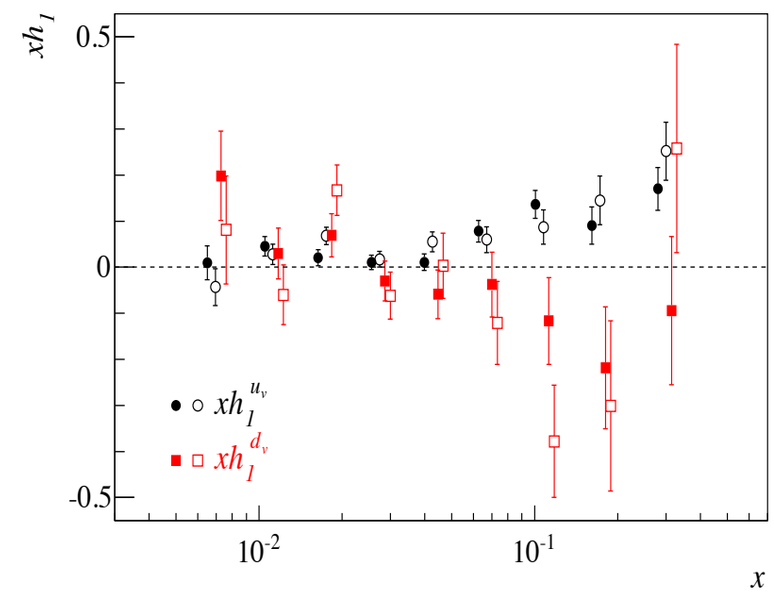
Anselmino et al., arXiv:1510.05389



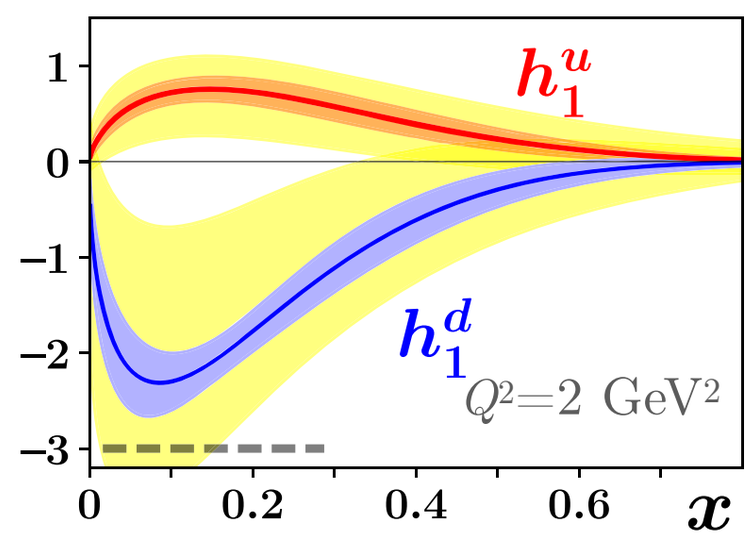
Radici, Bacchetta, arXiv:1802.05212



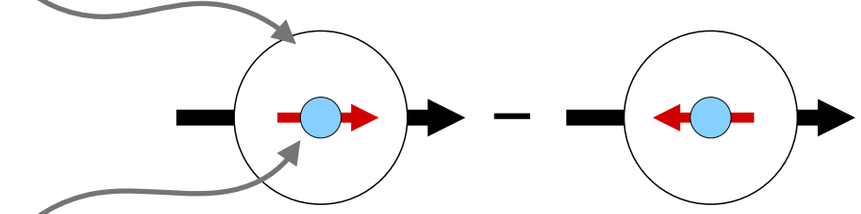
Martin, Bradamante, Barone, arXiv:1412.5946



Lin et al., arXiv:1710.09858



transversely polarized target

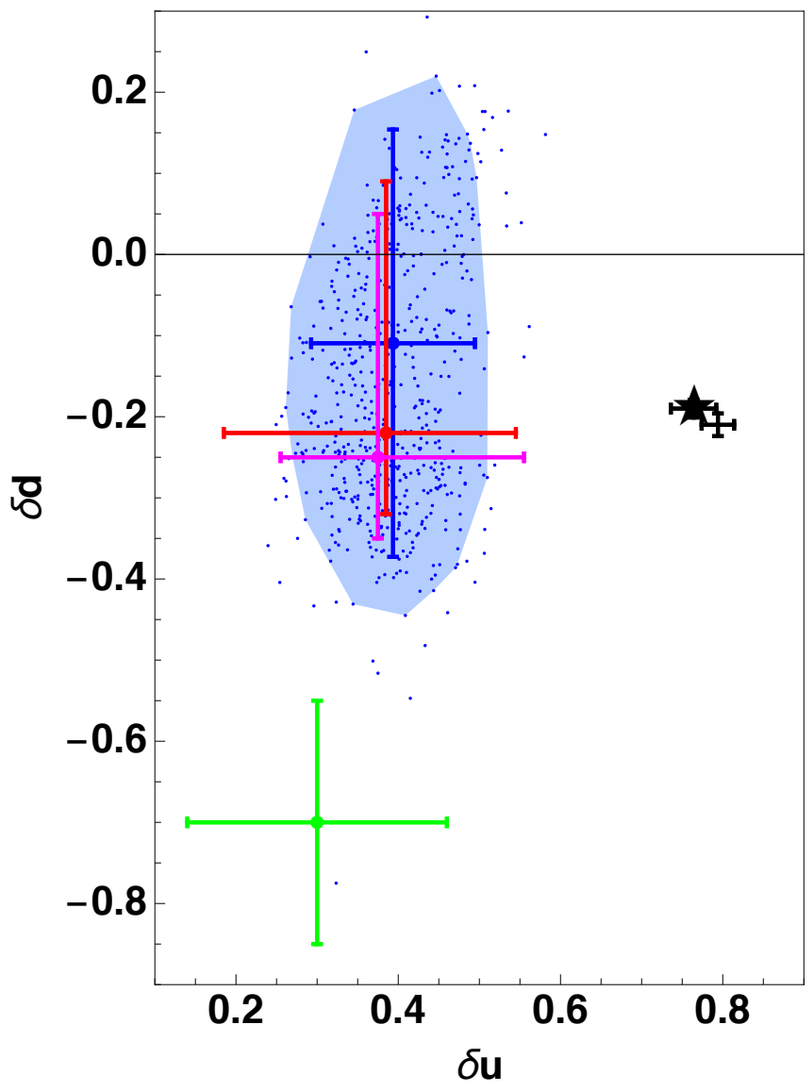


transversely polarized quark

TRANSVERSE SPIN

Tensor charge

$$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$



★ Alexandrou et al., arXiv:1703.08788

● Gupta et al., arXiv:1806.09006

● Anselmino et al., arXiv:1303.3822

● Kang et al., arXiv:1505.05589

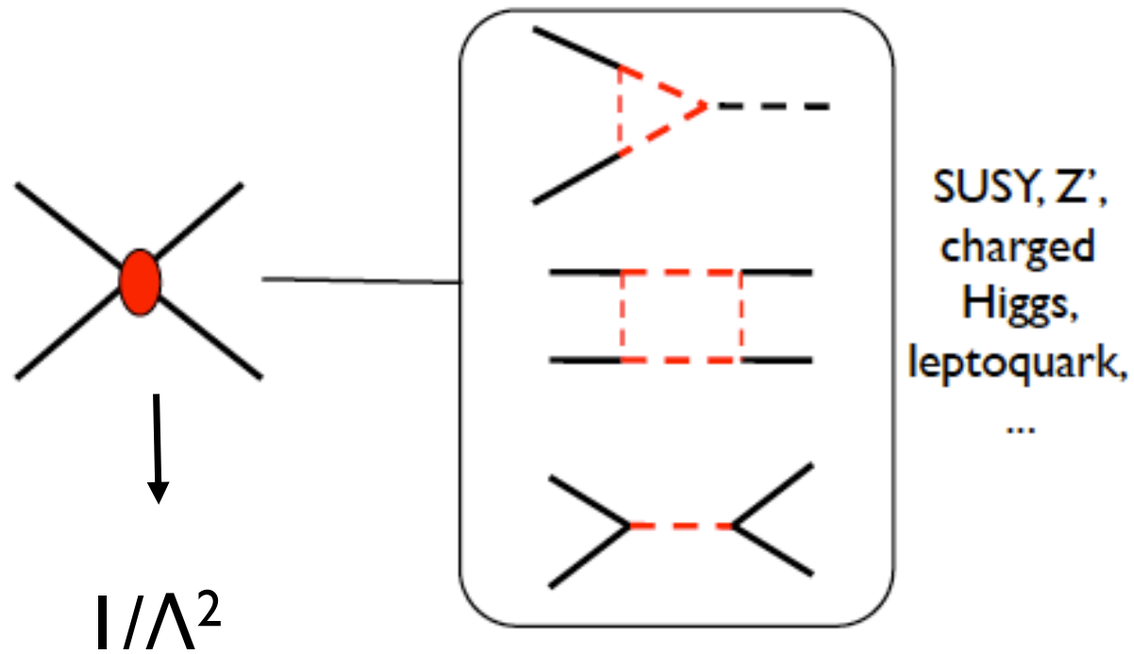
● Lin et al., arXiv:1710.09858

● Radici et al., arXiv:1802.05212

At the moment, there is a clear tension between extractions and lattice calculations

TENSOR CHARGE AND BSM

Tensor couplings, not present in the SM Lagrangian, could be the footprints of new physics at higher scales



$$\varepsilon_T \, g_T \approx M_W^2 \, / \, M_{BSM}^2$$

Bhattacharya et al, PRD 85 (12)

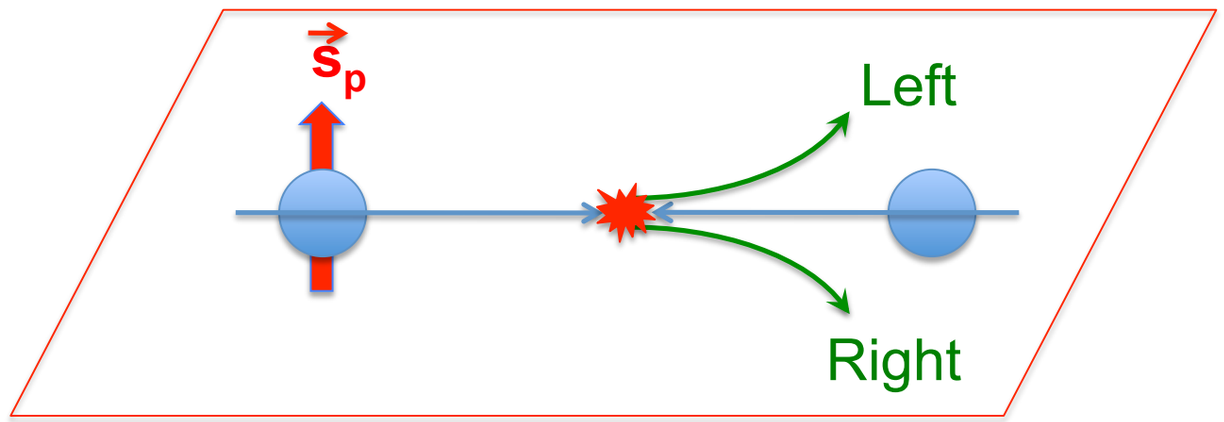
Pattie et al., P.R. C88 (13)

Current precision of 0.1% ⇒ [3-5] TeV bound for BSM scale

Knowledge of tensor charge is crucial

SINGLE SPIN ASYMMETRIES

Consider polarized hadron - hadron collisions



Count pions going to the right or to the left with respect to the spin direction

$$A_N \equiv \frac{\sigma(\vec{s}_P) - \sigma(-\vec{s}_P)}{\sigma(\vec{s}_P) + \sigma(-\vec{s}_P)}$$

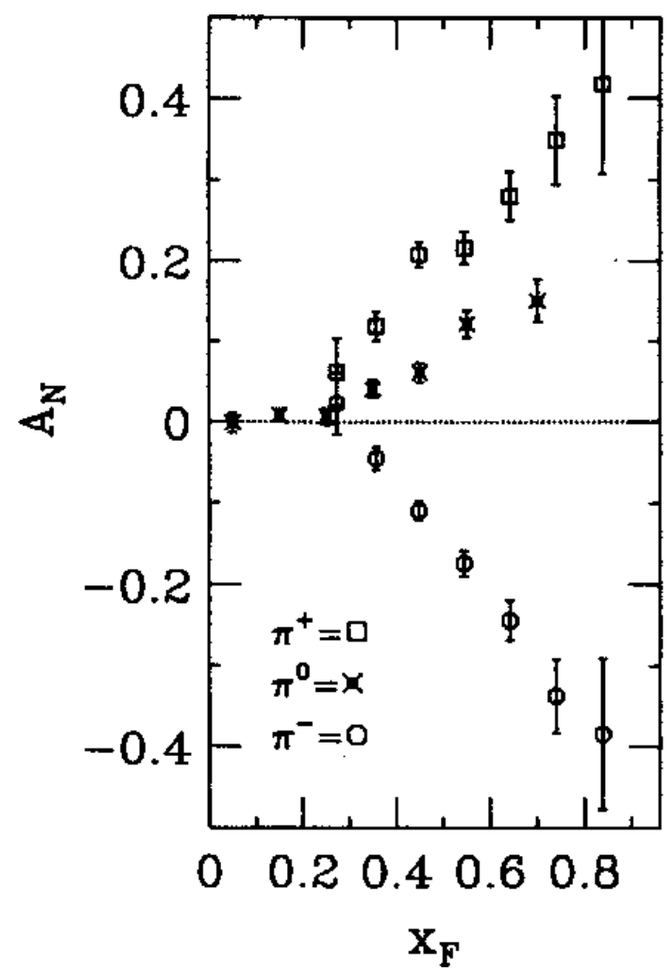
CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

Experiment proved this prediction wrong

QCD had a very simple prediction

$$A_N \propto \alpha_s \frac{m_q}{P_T} \to 0$$

Kane, Pumplin, Repko (1978)



$$A_N \simeq 40\%$$

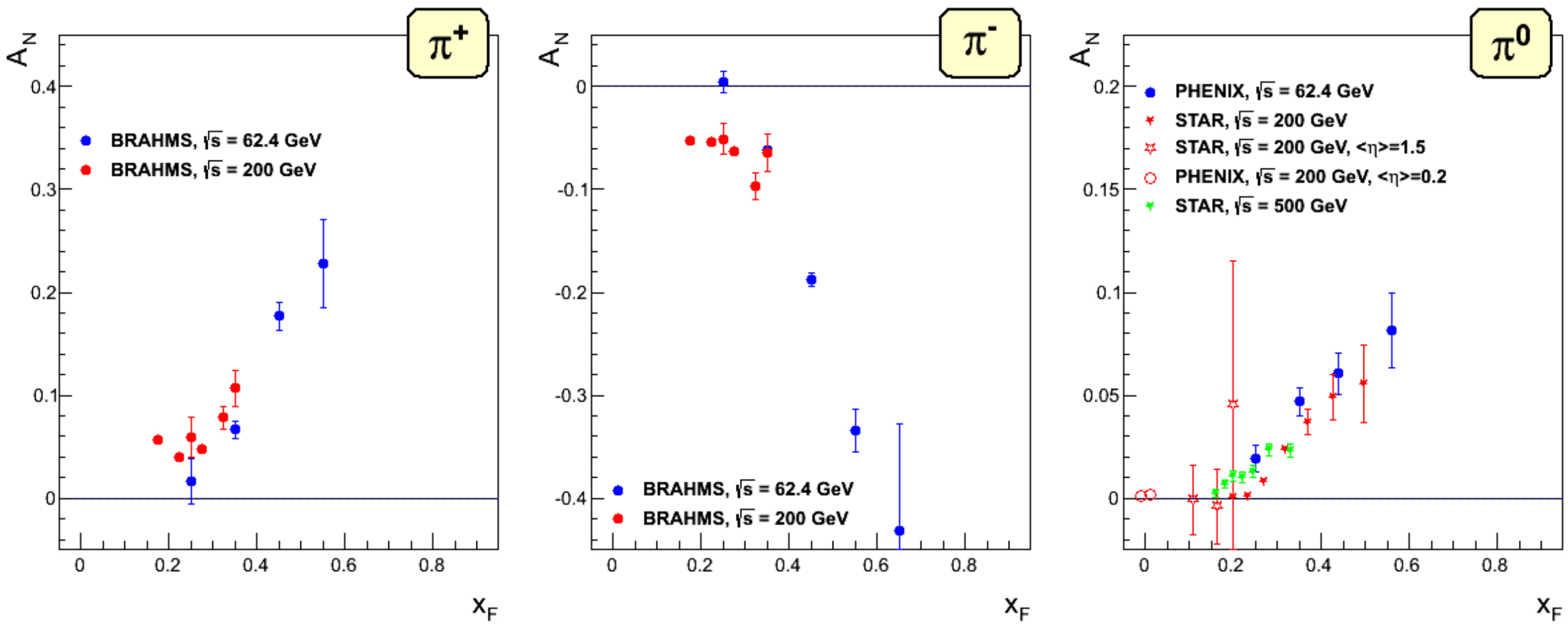
Fermilab experiment E704 (1991)

$$\sqrt{s} \simeq 19 \text{ (GeV)}$$

CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

Asymmetry survives with growing collision energy

RHIC: STAR, BRAHMS, PHENIX



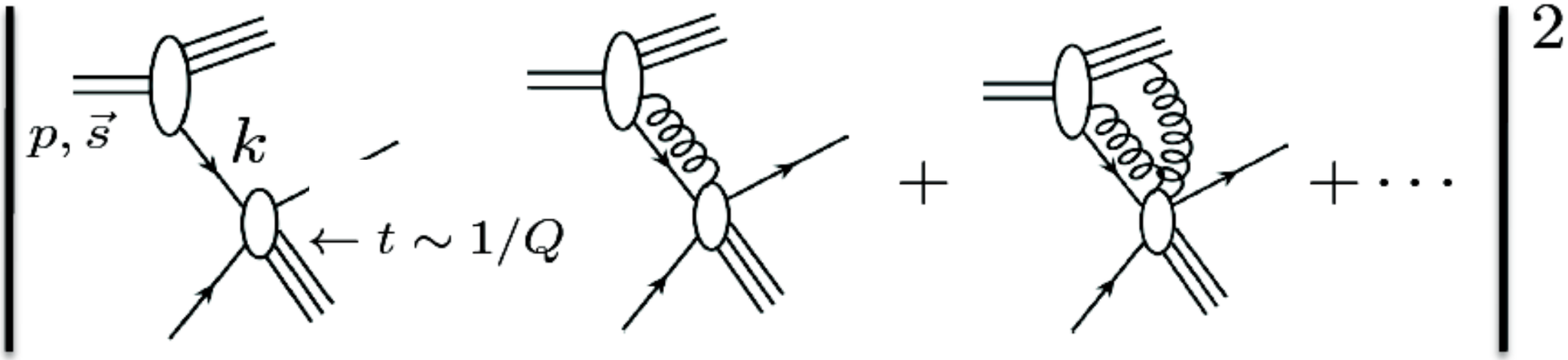
"The RHIC SPIN Program: Achievements and Future Opportunities", Aschenauer et al (15)

FAILURE OF QCD?


QCD
BETTER
UNDERSTANDING OF QCD!

BETTER UNDERSTANDING OF QCD

$\sigma(Q, \vec{s}) \propto$



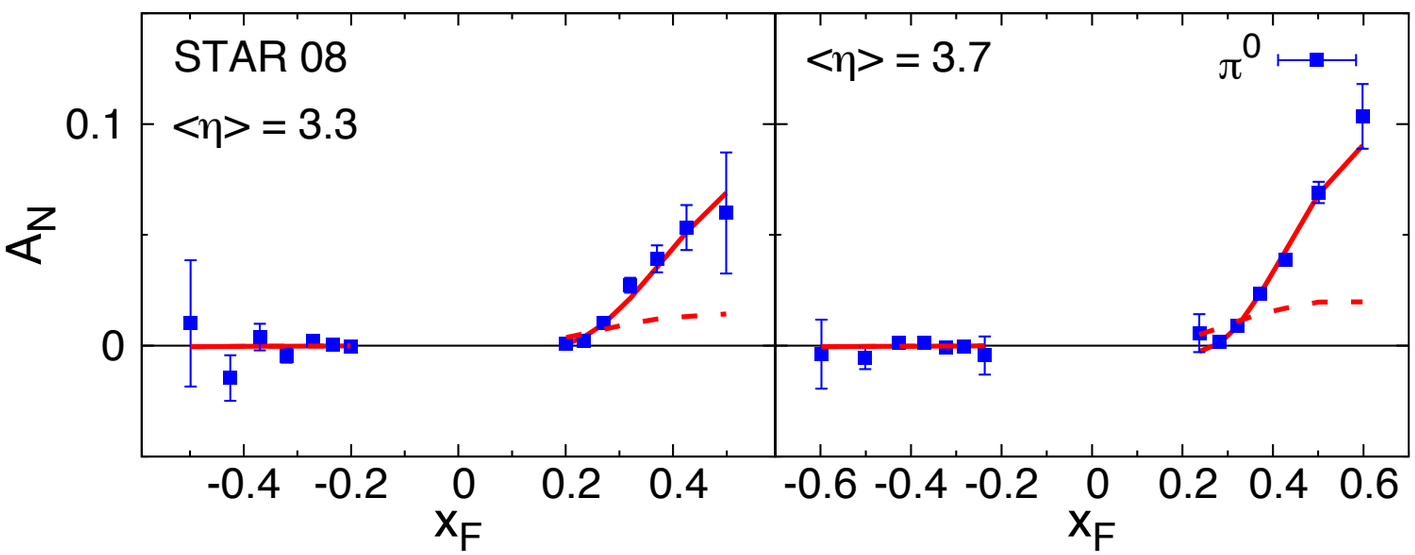
Qiu, Sterman (1990)

Multi-parton correlations (twist-3 functions) contribute to the cross section and are dominant for asymmetries

Collinear objects related to TMDs via Operator Product Expansion

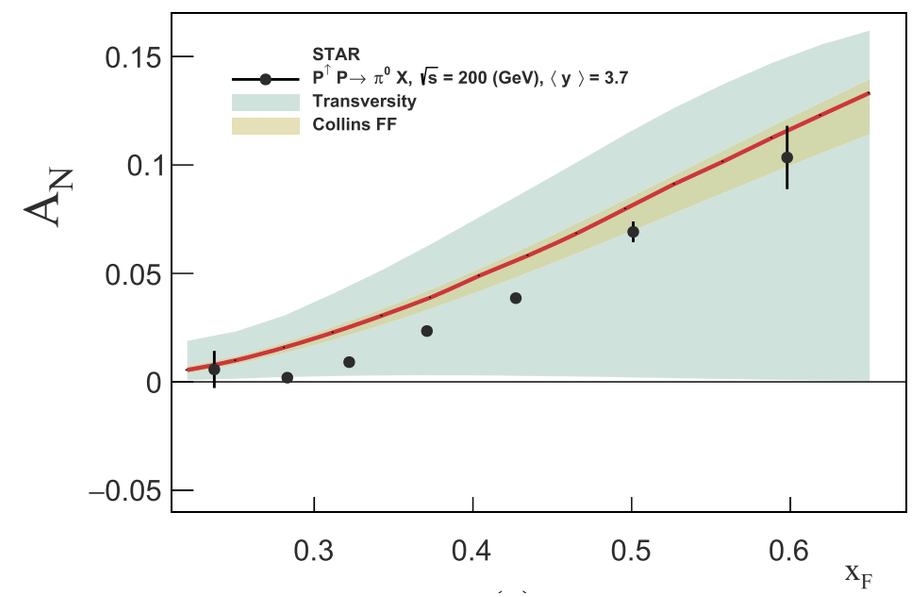
TOWARDS THE SOLUTION OF 40 YEAR OLD PUZZLE

Kanazawa, Koike, Metz, Pitonyak PRD 89 (2014)



Explanation using fit of twist-3 fragmentation functions

Gamberg, Kang, Pitonyak, Prokudin PLB 770 (2017)



Prediction of A_N at STAR using only SIDIS and e^+e^- data information only

Spin physics is making a lot of progress

Spin physics can have an impact also on BSM searches

3D STRUCTURE

TMD FACTORIZATION

W term

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int\frac{d\boldsymbol{b}_\perp^2}{4\pi}J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a\big(x,z^2\boldsymbol{b}_\perp^2;\mu^2\big)\,\tilde{D}_1^{a\to h}\big(z,\boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+\,Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big)+\mathcal{O}\big(M^2/Q^2\big)$$

The Y term guarantees that the calculation at high P_{hT} agrees with perturbative calculation done with collinear factorization

$$\widetilde{f}_1^a(x,b_T;\mu^2) = \sum_i\big(\tilde{C}_{a/i}\otimes f_1^i\big)(x,b_*;\mu_b)e^{\tilde{S}(b_*;\mu_b,\mu)}e^{g_K(b_T)\ln\frac{\mu}{\mu_0}}\hat{f}^a_{\rm NP}(x,b_T)$$

collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

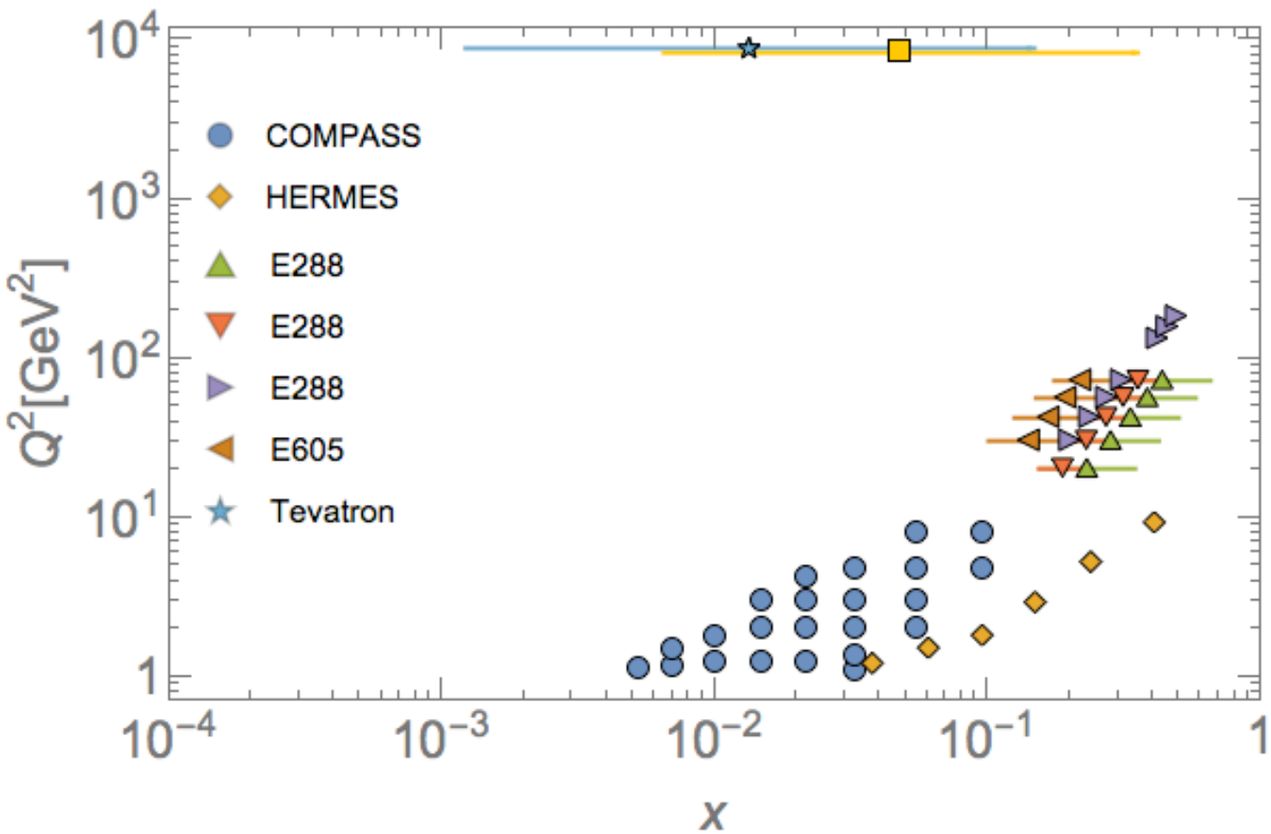
see, e.g., Rogers, Aybat, PRD 83 (11),
Collins, "Foundations of Perturbative QCD" (11)

other possible schemes, e.g.,
Laenen, Sterman, Vogelsang, PRL 84 (00)
Bozzi, Catani, De Florian, Grazzini, NPB737 (06)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

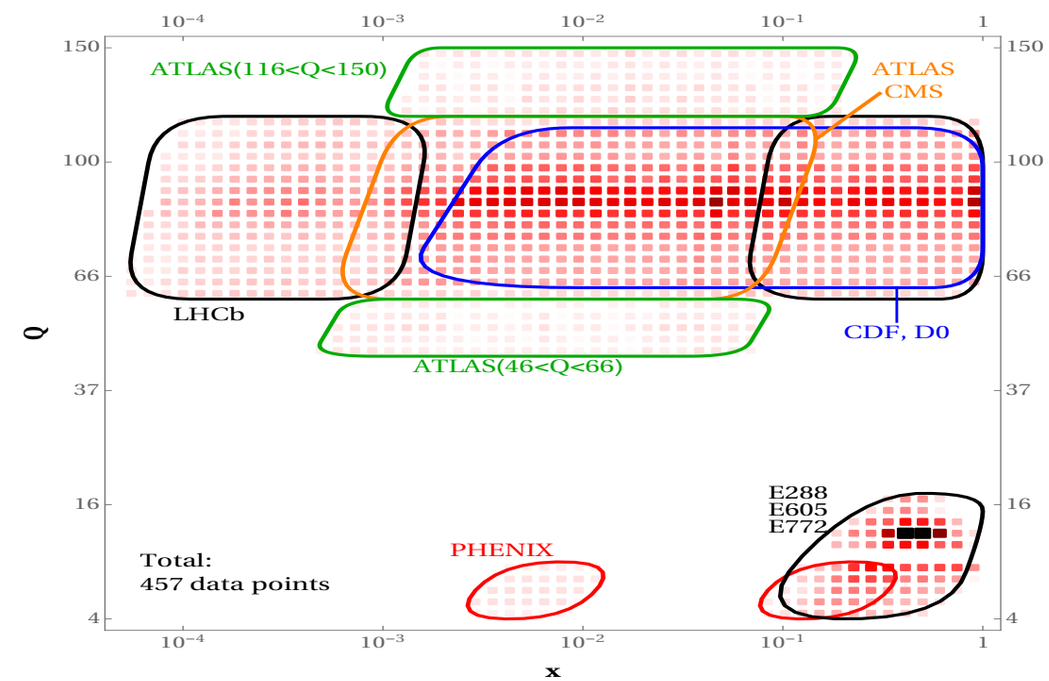
TMD FITS OF UNPOLARIZED DATA

	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	457

x–Q² COVERAGE

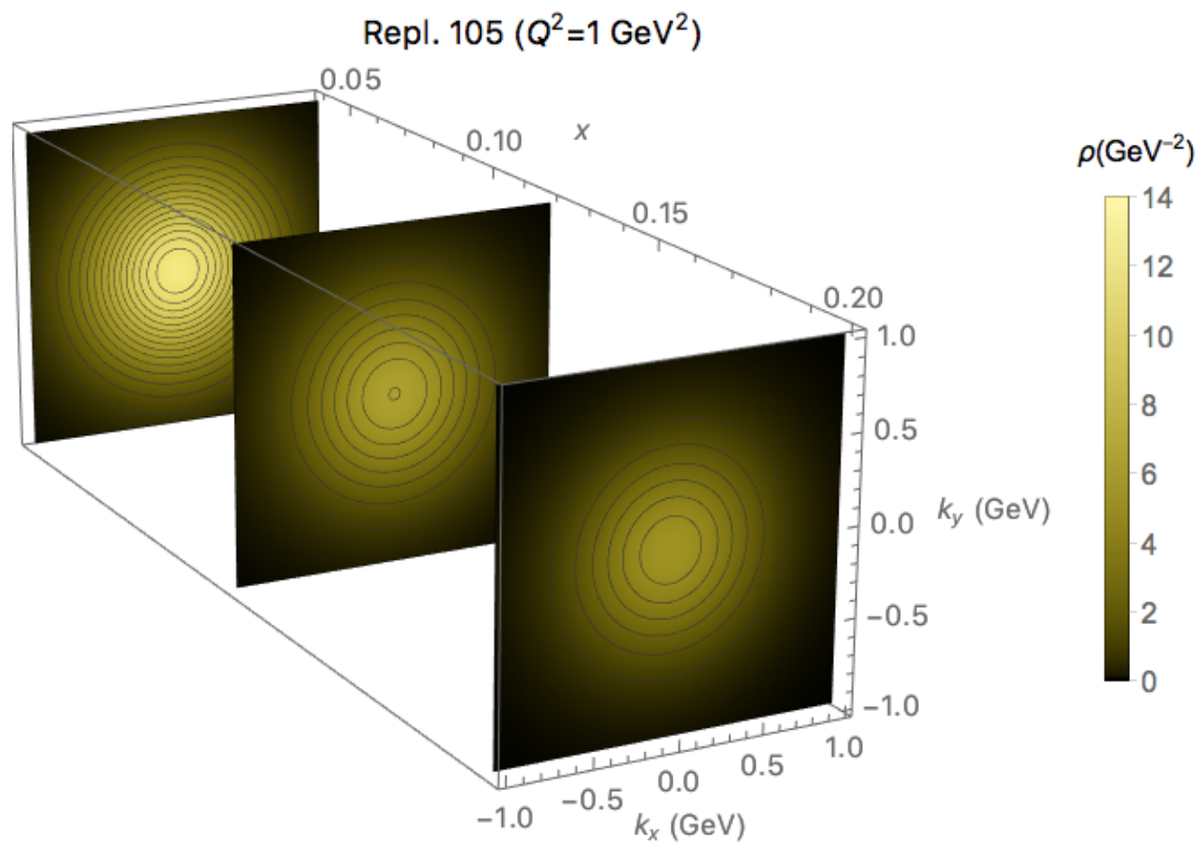


Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

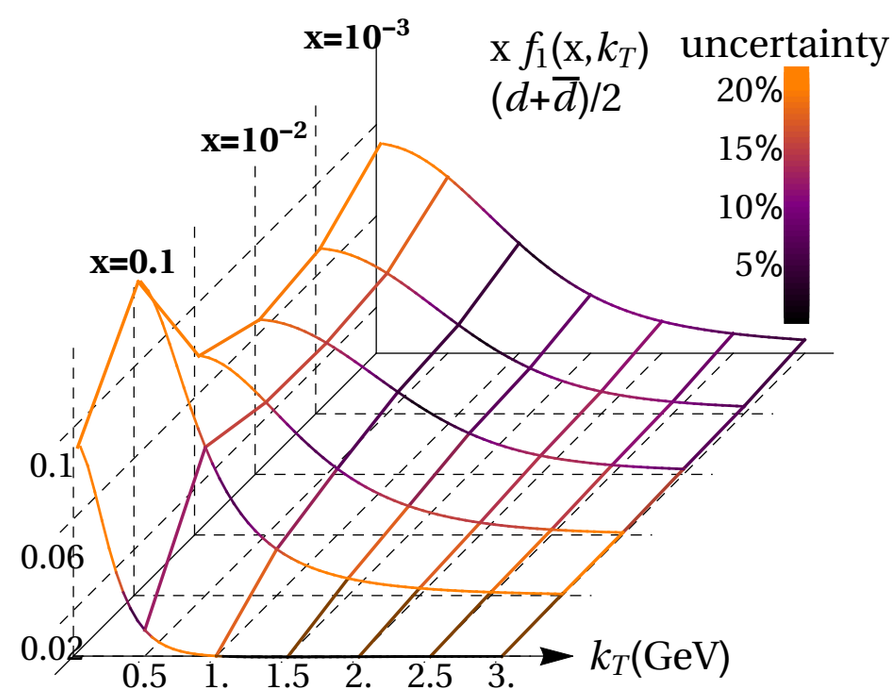


Bertone, Scimemi, Vladimirov, arXiv:1902.08474

3D DISTRIBUTIONS EXTRACTED FROM DATA



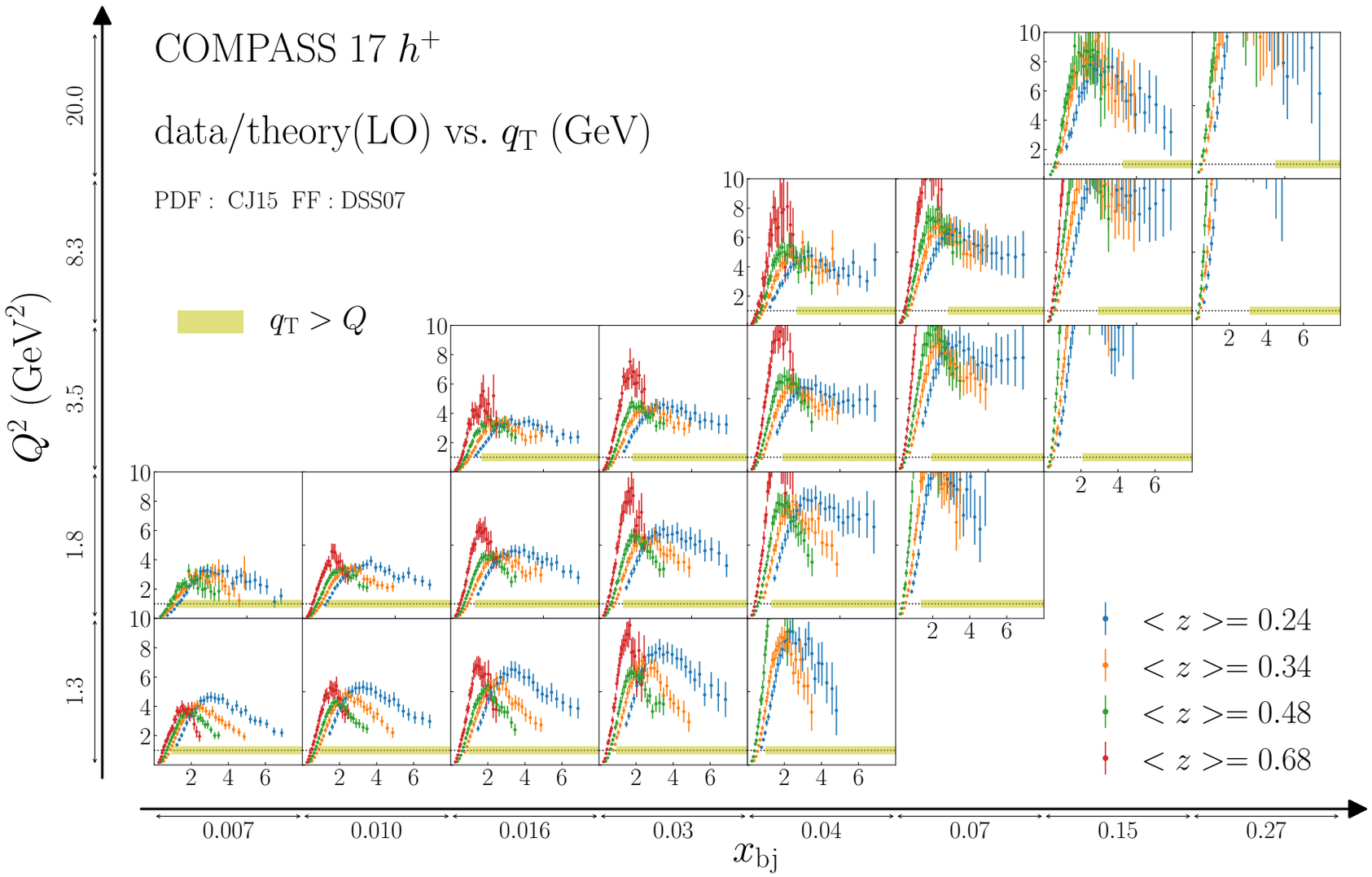
Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157



Bertone, Scimemi, Vladimirov, arXiv:1902.08474

PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

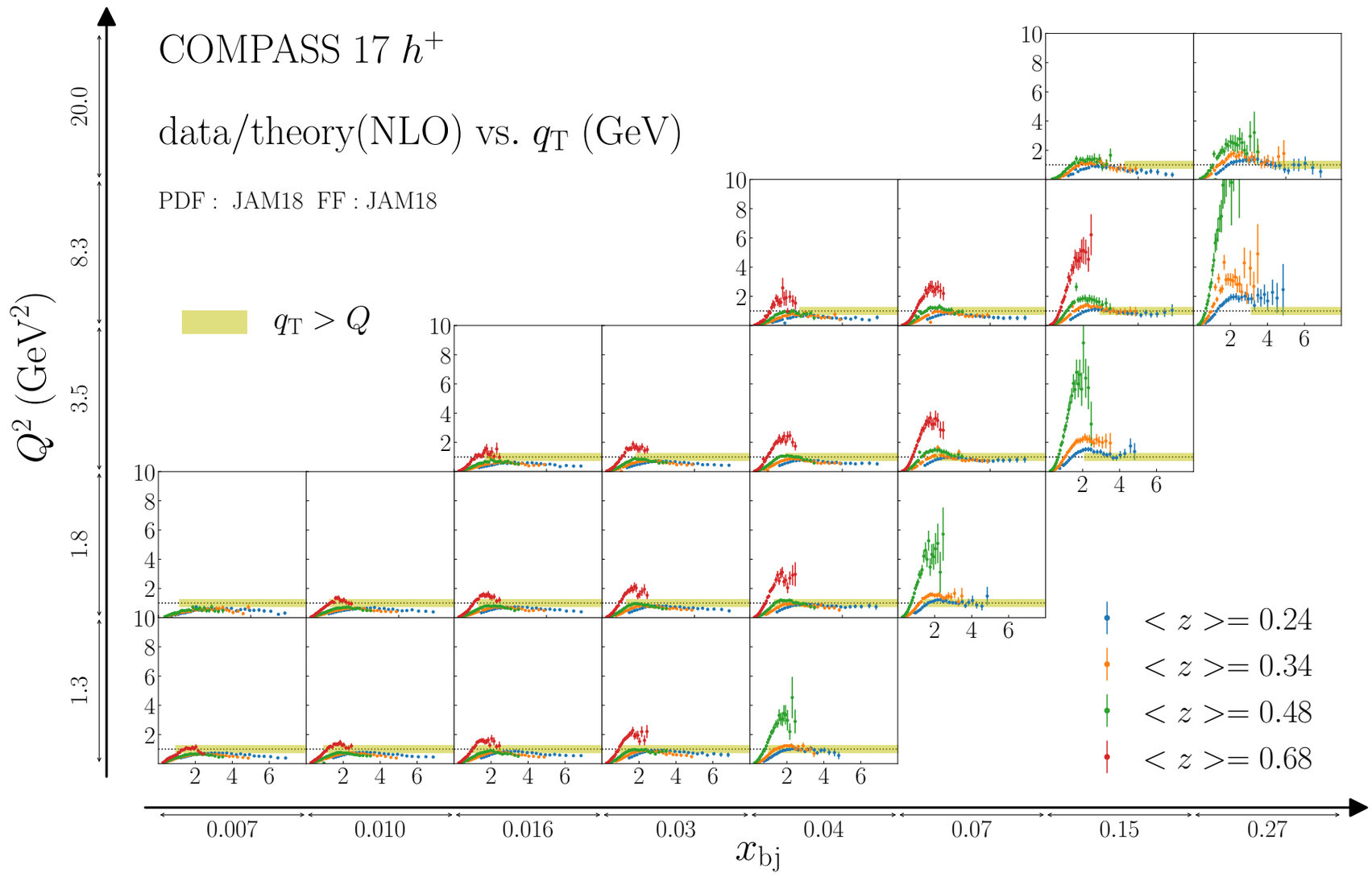
Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



At high q_T, the collinear formalism should be valid, but large discrepancies are observed

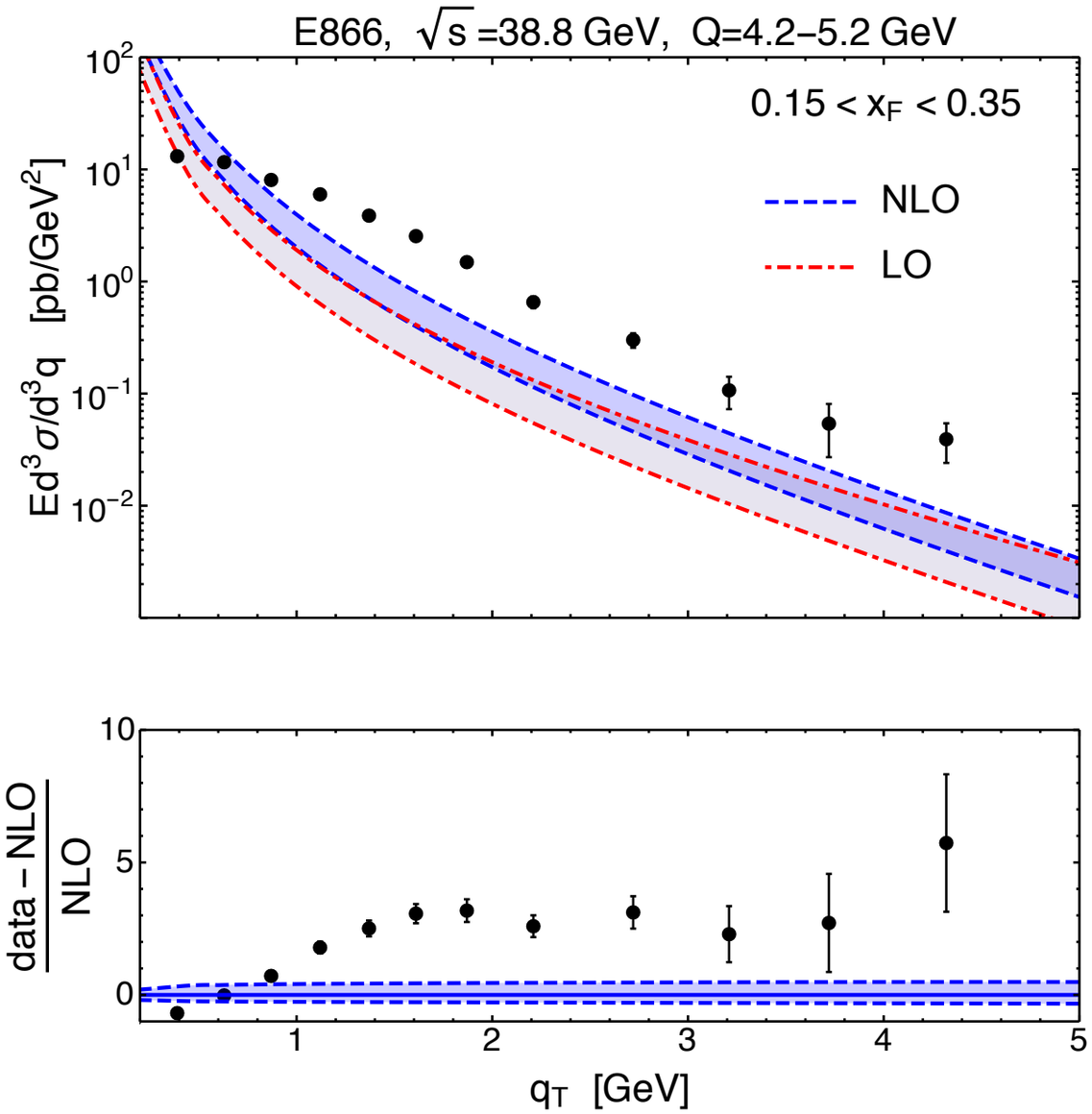
PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

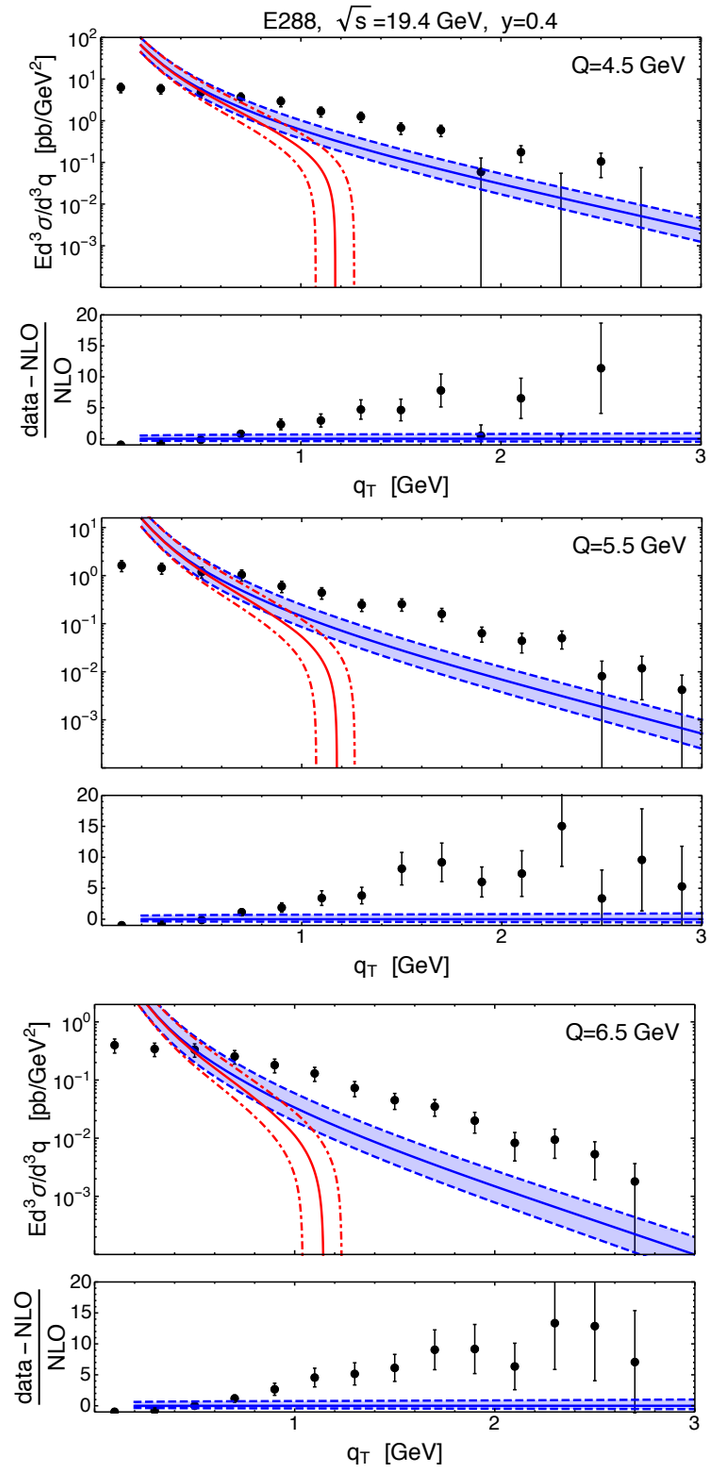
Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



The discrepancies could be largely resolved by sharply modifying the gluon collinear fragmentation function

However, large discrepancies are found also in low-energy DY scattering data

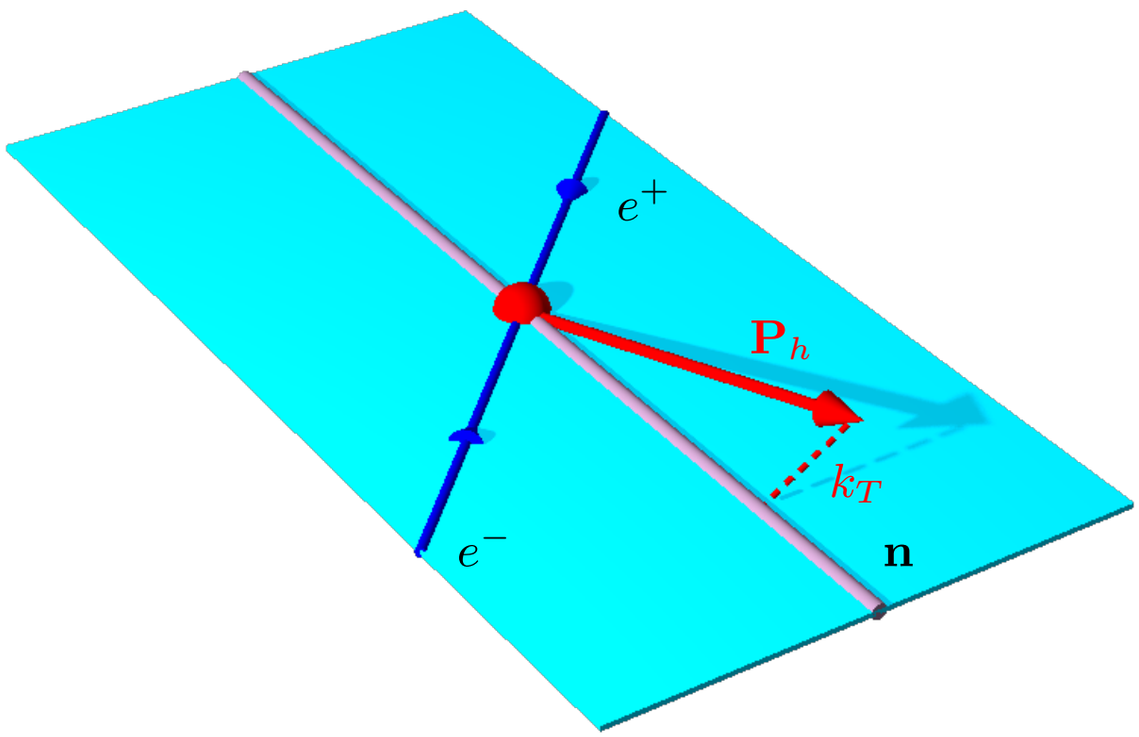


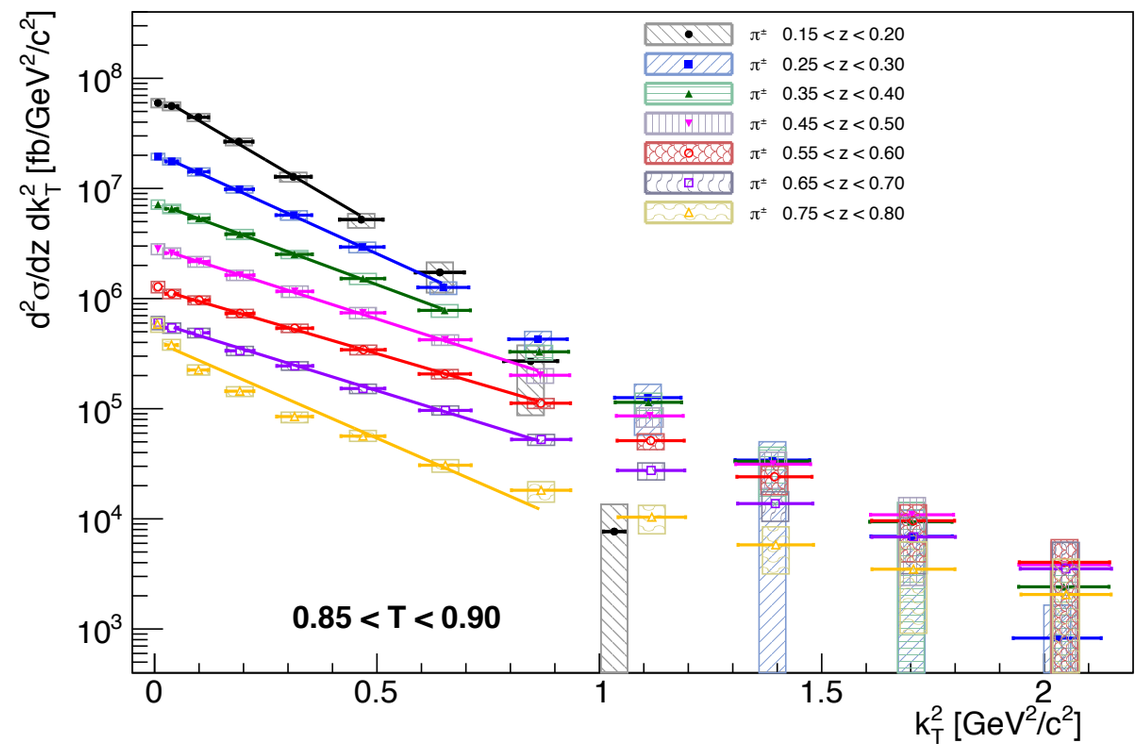


Bacchetta, Bozzi, Lambertsen, Piacenza, Steinglechner, Vogelsang arXiv:1901.06916

TRANSVERSE MOMENTUM IN FRAGMENTATION FUNCTIONS

Seidl et al., arXiv:1807.02101

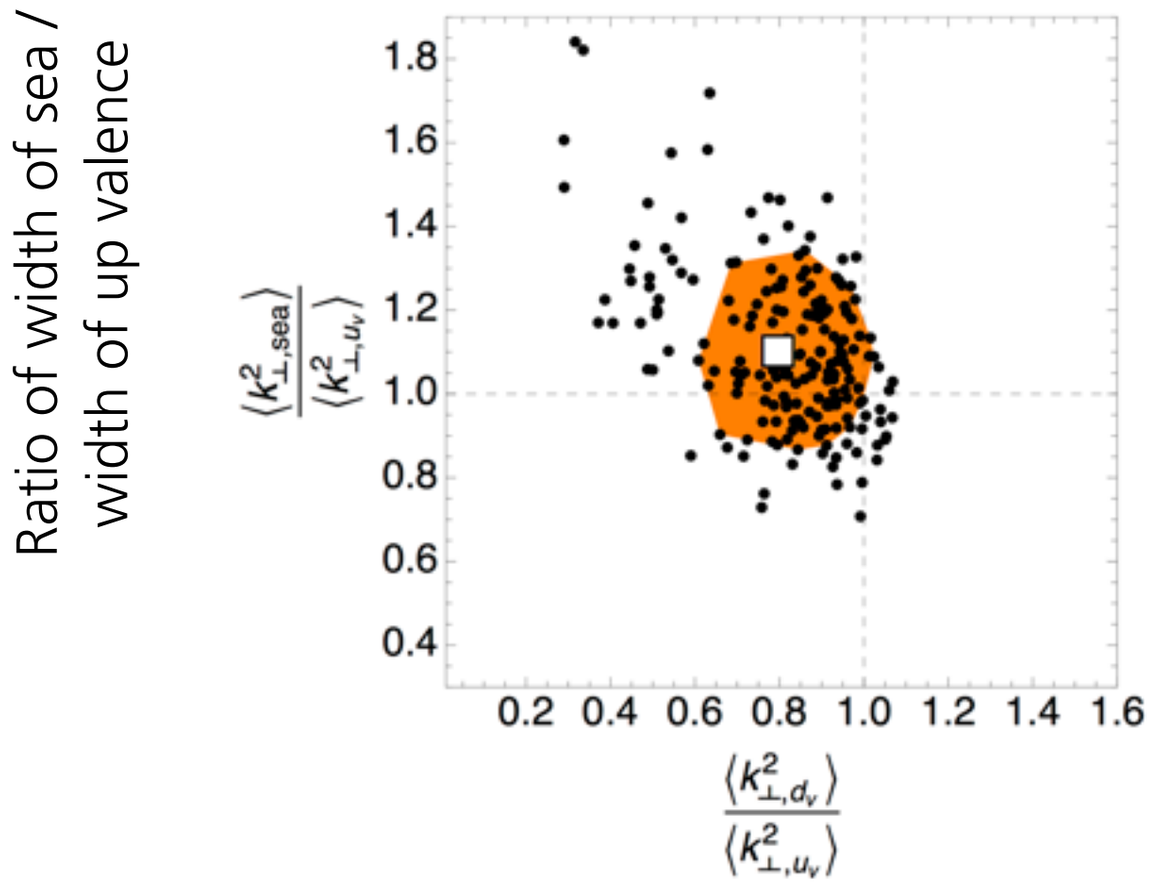


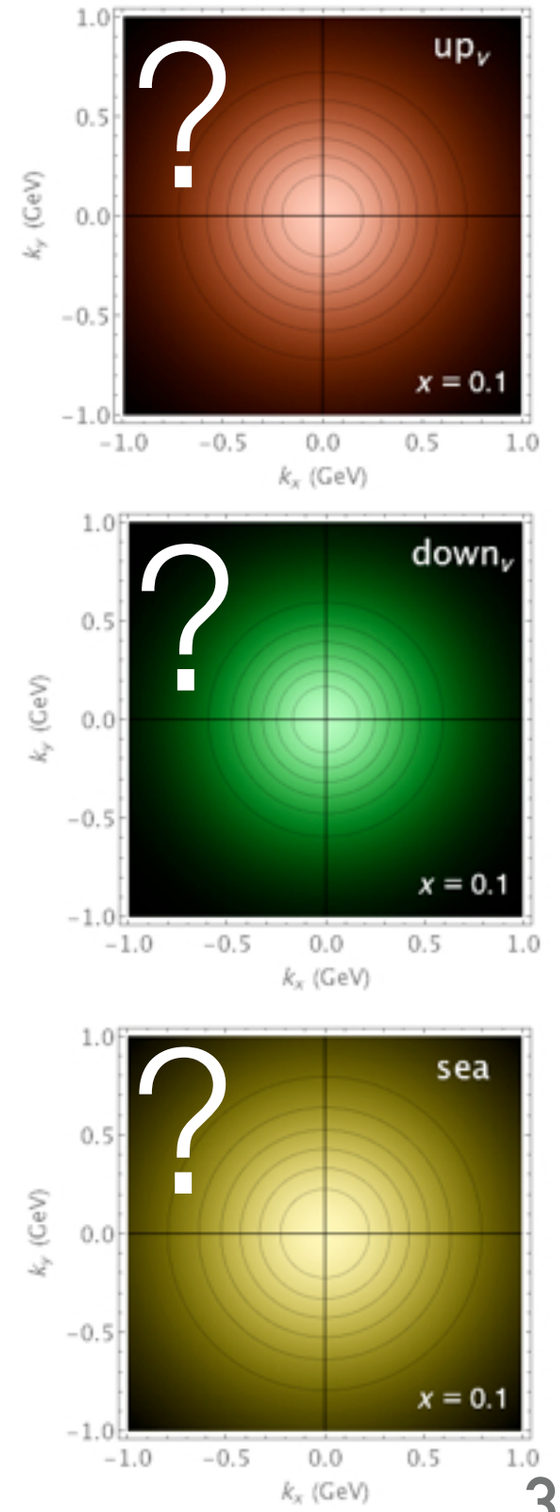


First direct measurement of TMD effects in fragmentation functions
Makes use of thrust axis: the formalism should take it into account

FLAVOR DEPENDENCE OF TMDS

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

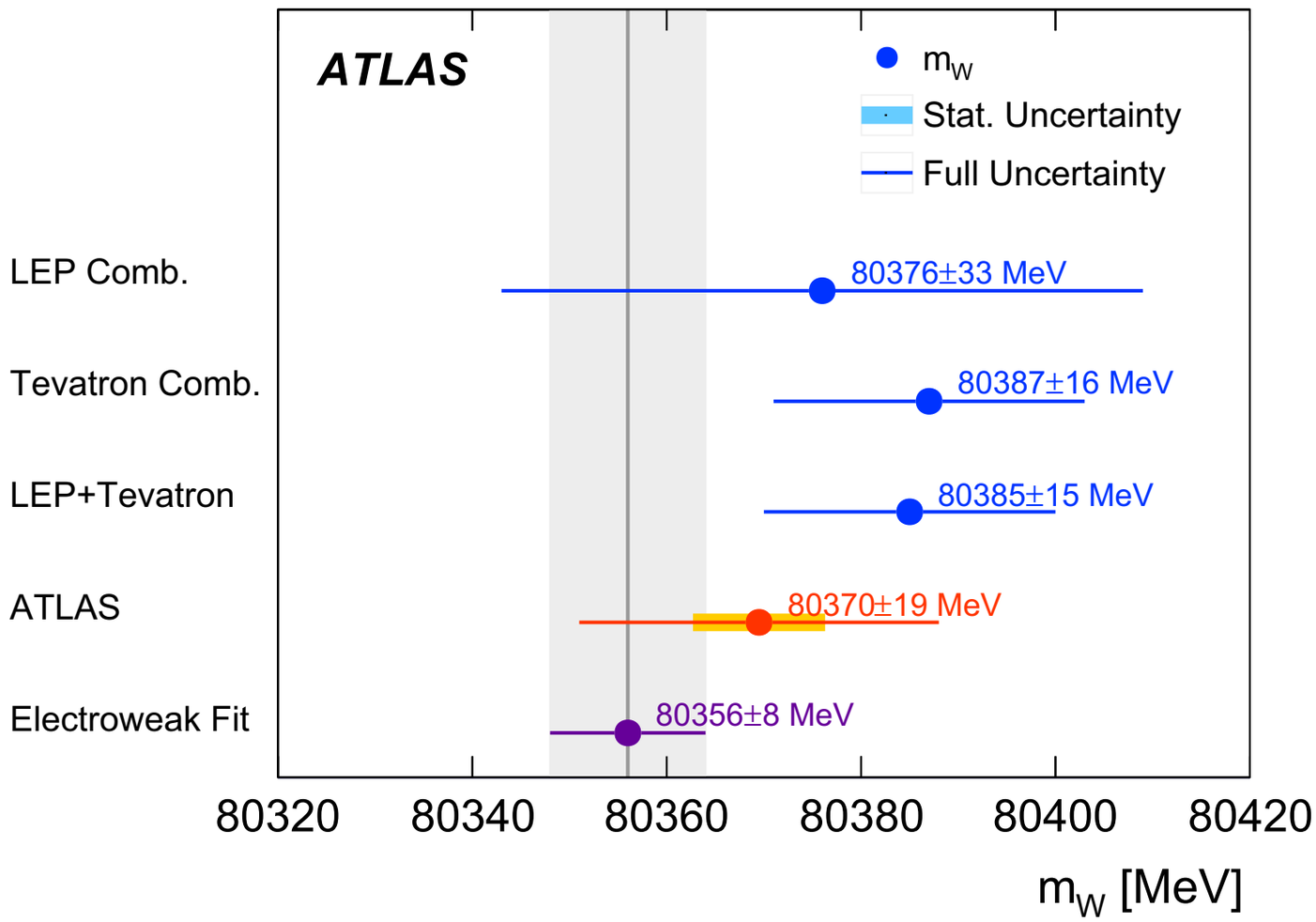




There is room for flavour dependence, but we don't control it well

IMPACT ON W MASS DETERMINATION

ATLAS Collab. arXiv:1701.07240



All analyses assume that TMDs are not flavour dependent.
What happens if they are?

$$m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

IMPACT ON W MASS DETERMINATION

Bacchetta, Bozzi, Radici, Ritzmann, Signori, arXiv:1807.02101

Try some judicious choices of flavour dependent widths and check

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27

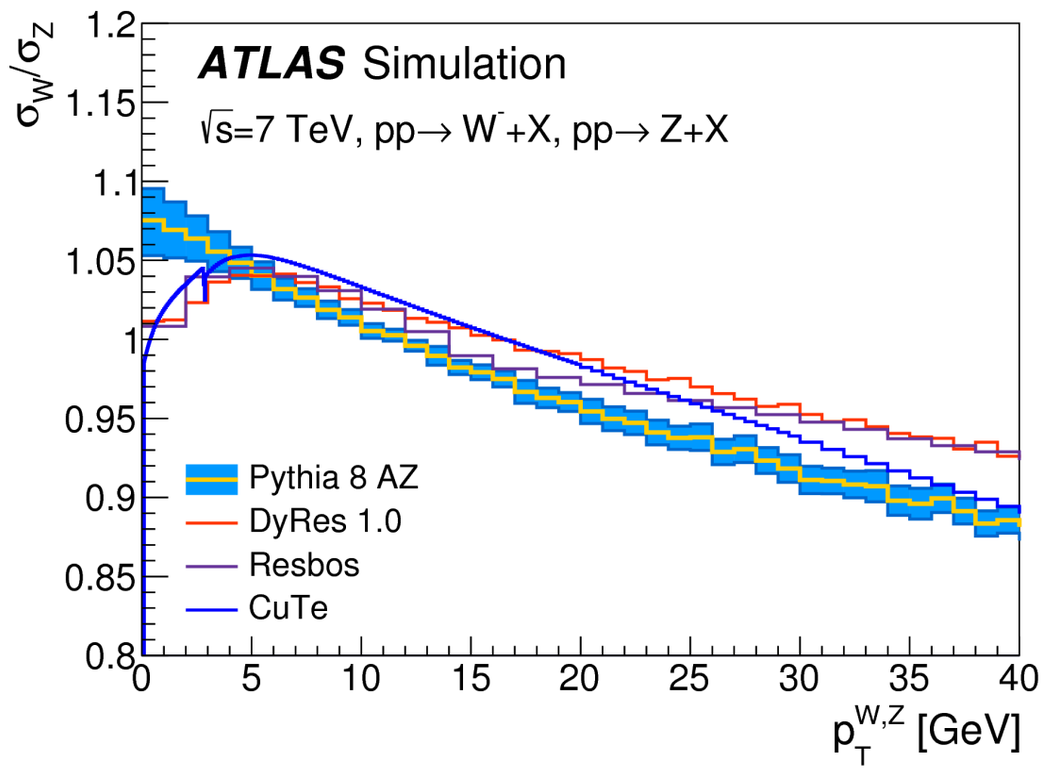
narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
medium, narrow, large

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass

3D STRUCTURE AND MC GENERATORS

from A. Apyan's talk at LHC EW Precision sub-group workshop
https://indico.cern.ch/event/801961/

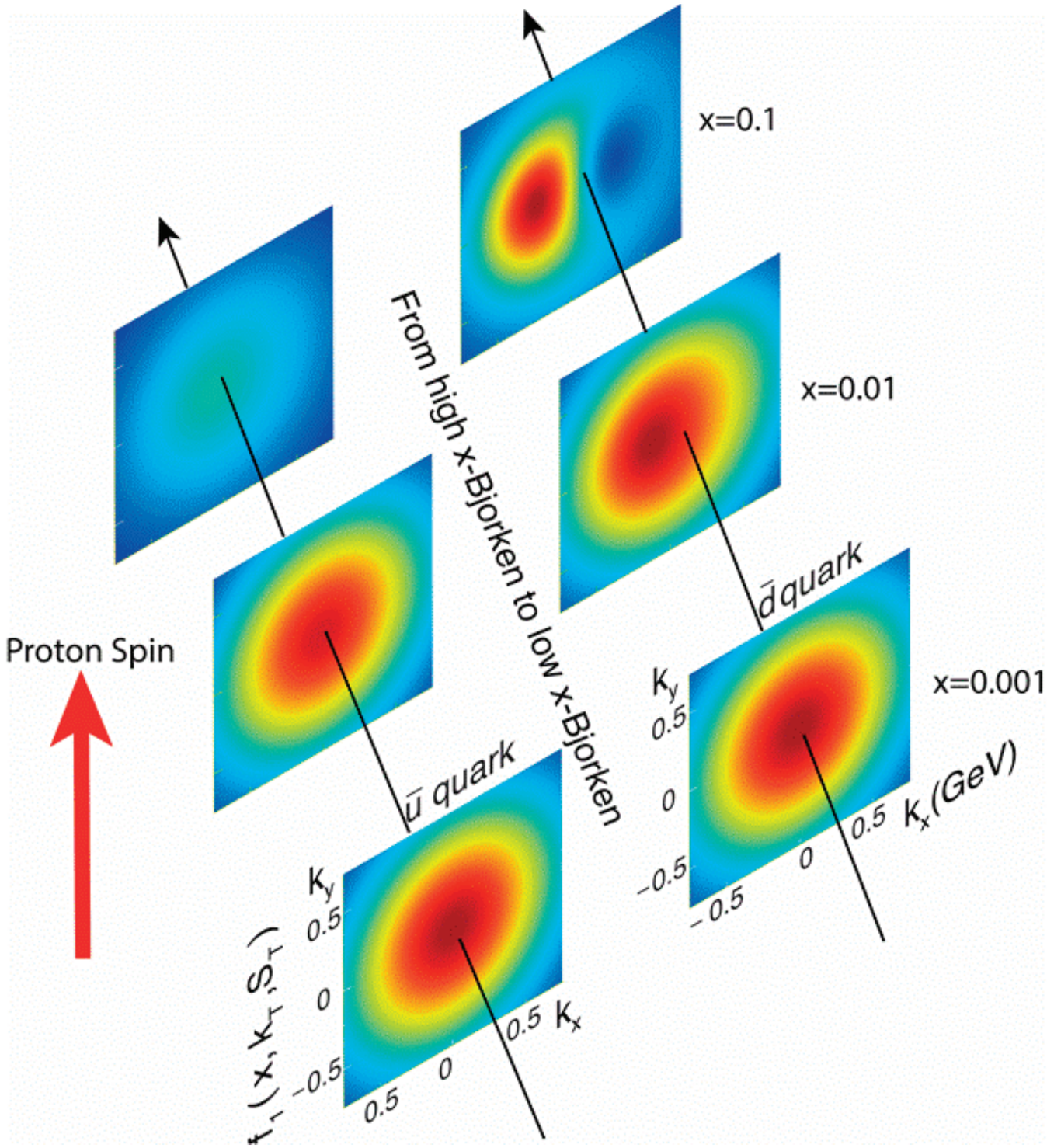


also
ResBos2
Radish
SCETlib
...

Precision measurements require well-tuned MC tools. Important effects at low pT come from nonperturbative TMD components

Efforts are going also into including spin in PYTHIA

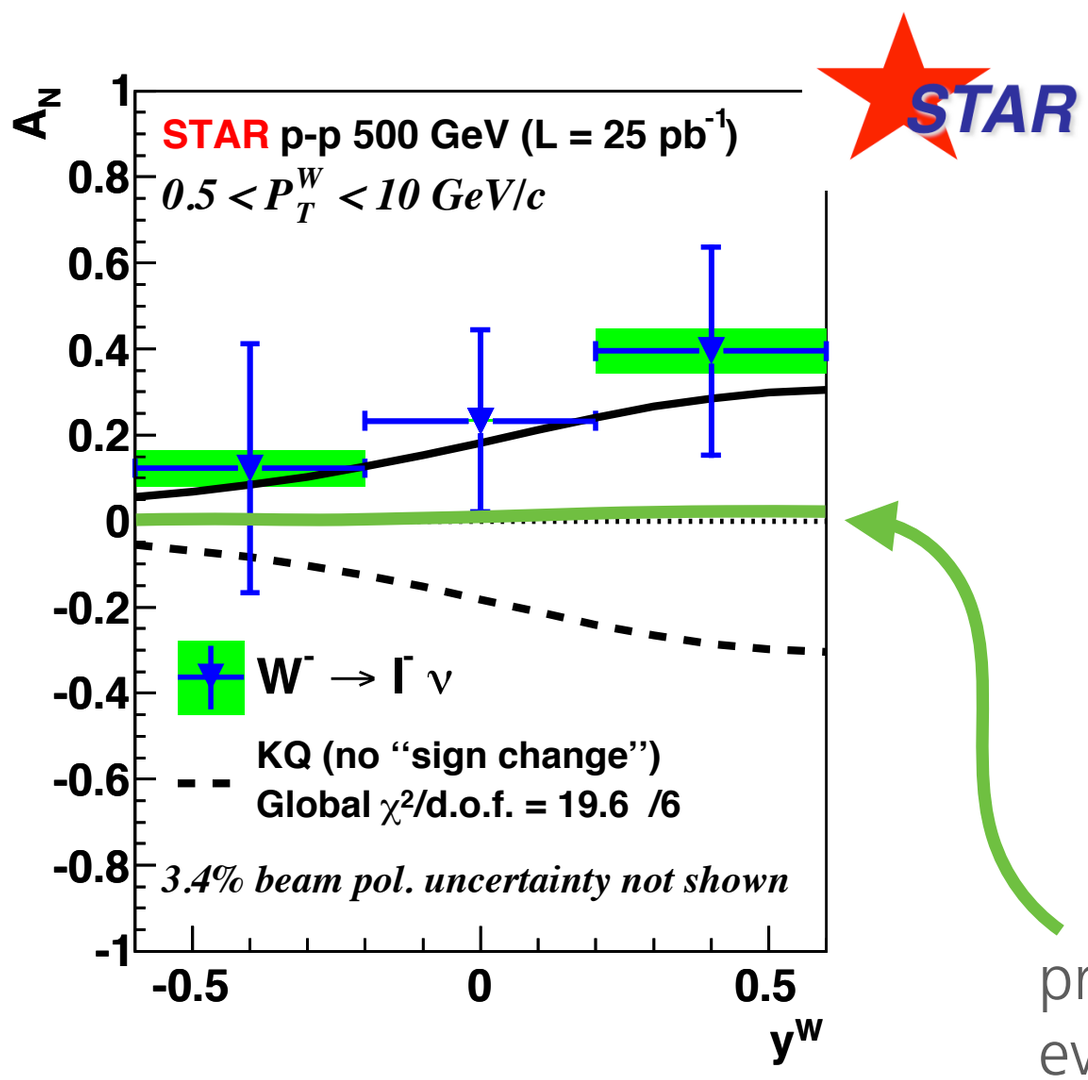
SIVERS DISTORTION



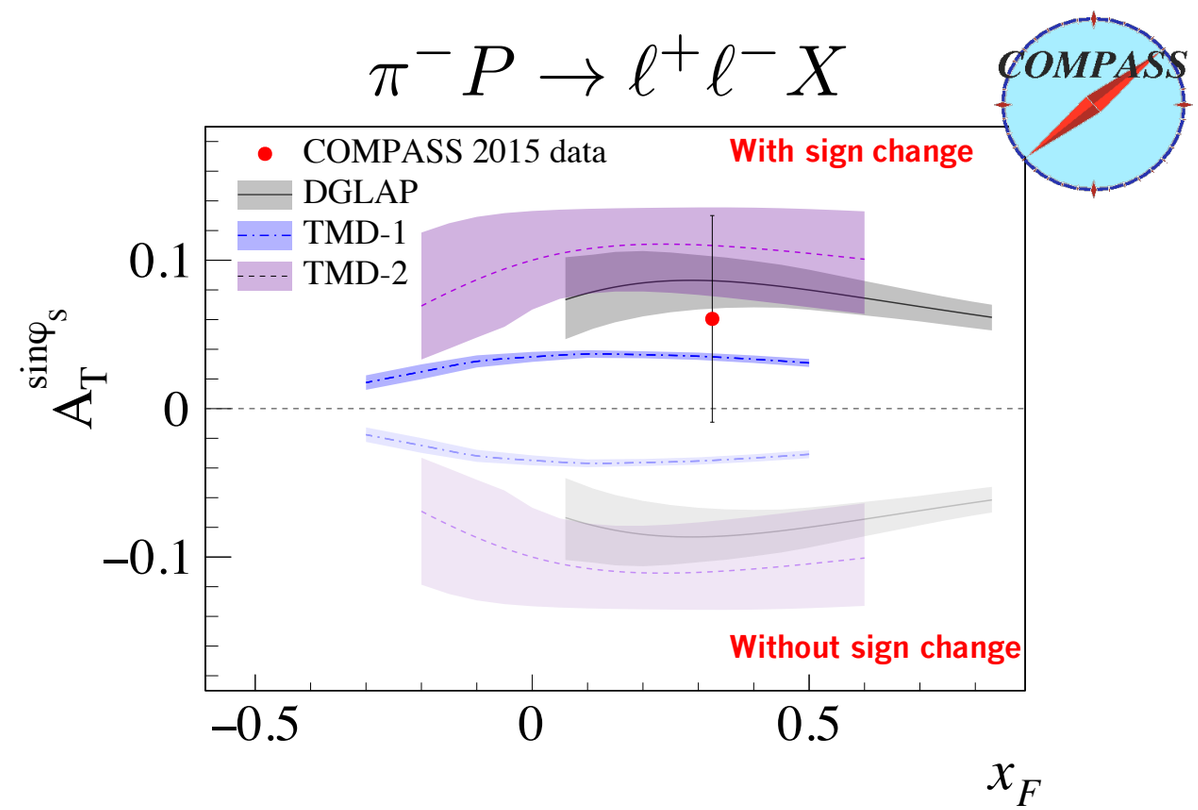
SIVERS FUNCTION SIGN CHANGE

Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)



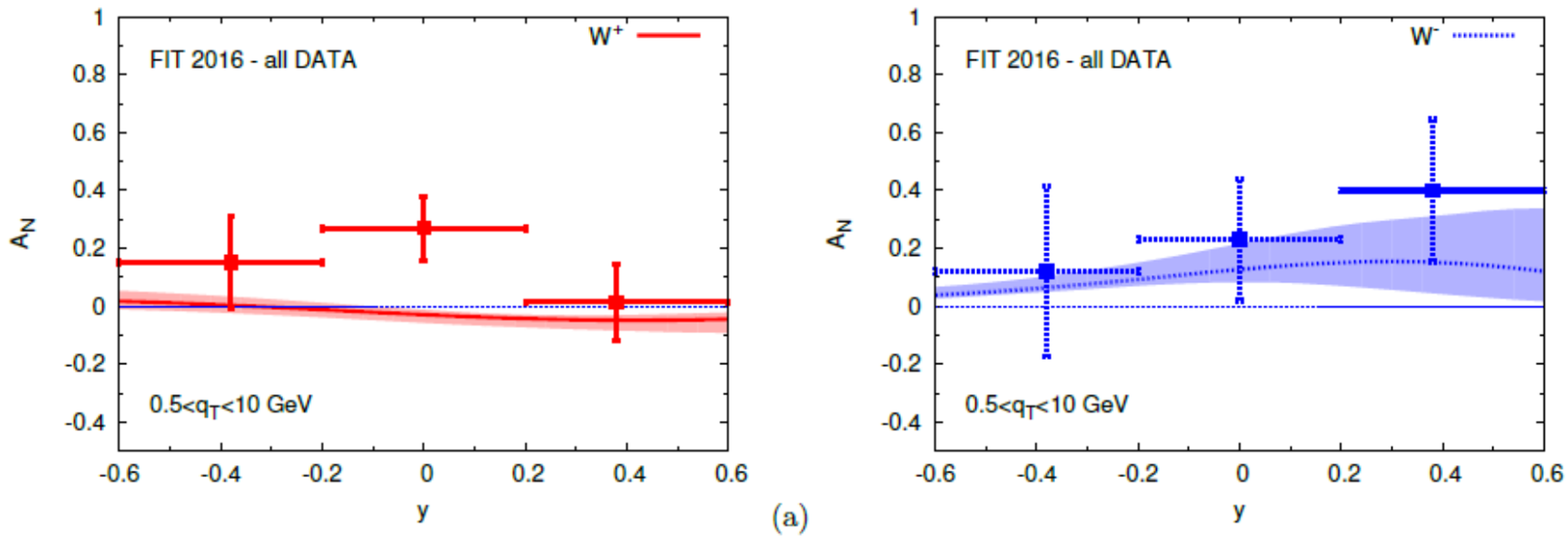
STAR Collab. arXiv:1511.06003



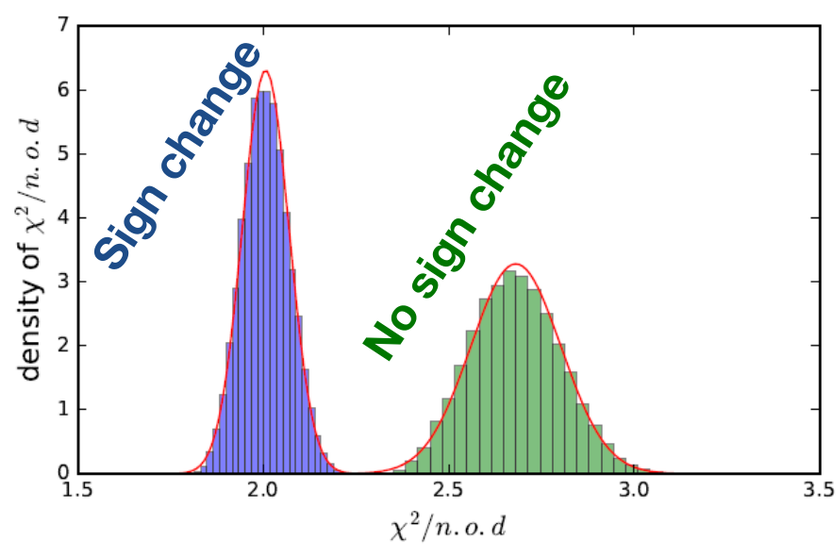
prediction with TMD evolution equations

SIVERS FUNCTION SIGN CHANGE

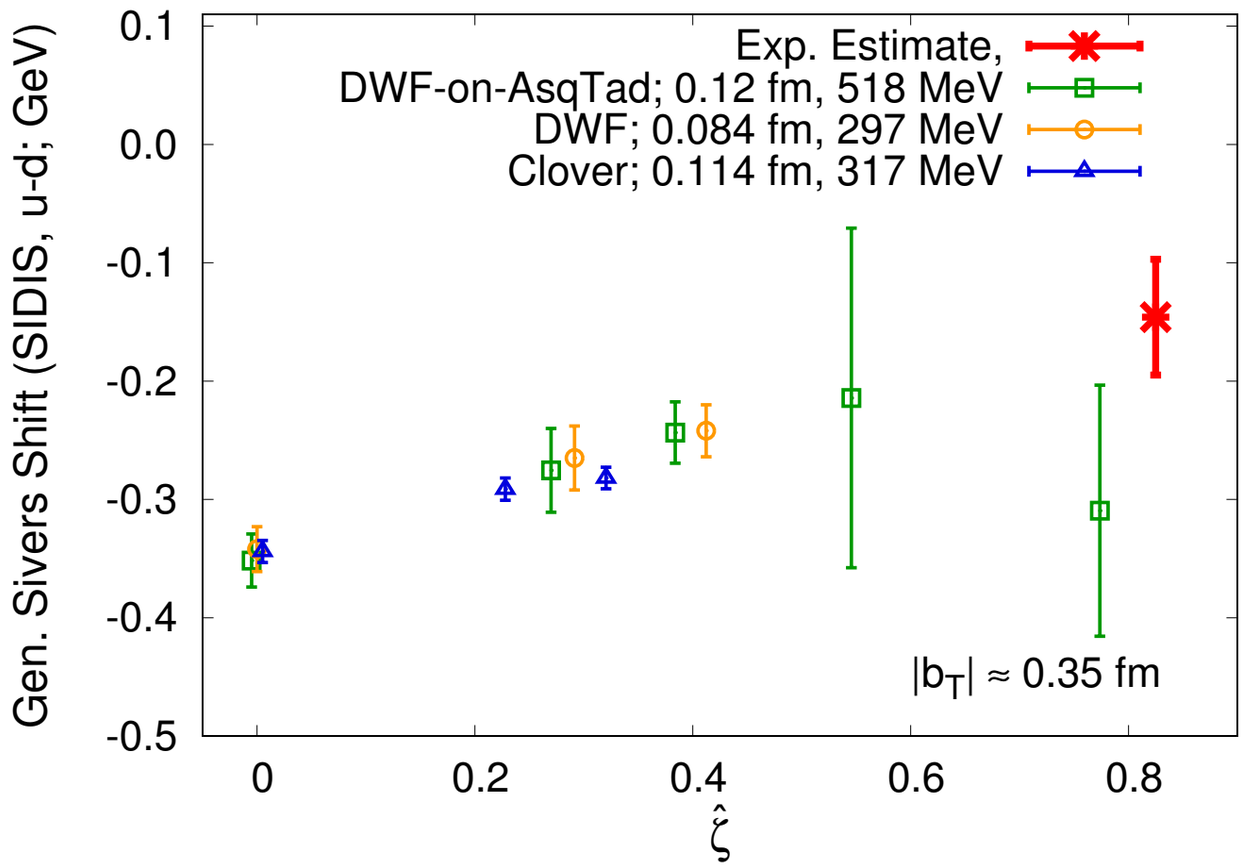
Anselmino, Boglione, D'Alesio, Murgia, Prokudin JHEP 1704 (2017) 046



(a)



SIVERS SHIFT IN LATTICE QCD



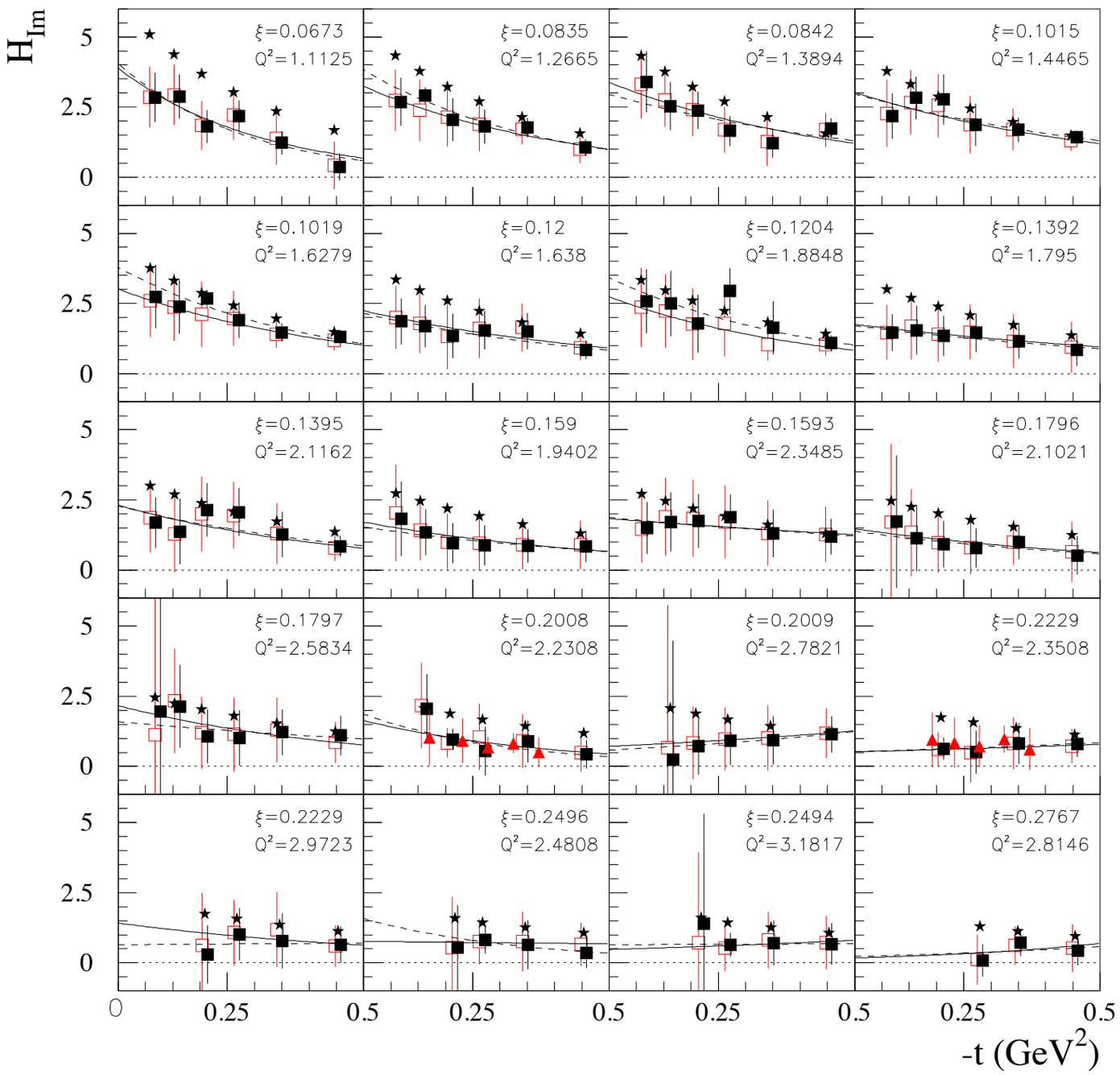
Yoon et al., arXiv:1706.03406

Pioneering lattice studies are in agreement with phenomenology

Fast progress in TMD determinations is taking place, but still many open questions

As TMDs are known better and better, they can be used to improve high-energy precision measurements

GPDS AND THE WAY TO 3D IMAGING



Compton Form Factors are extracted from data

Jefferson Lab

hermes

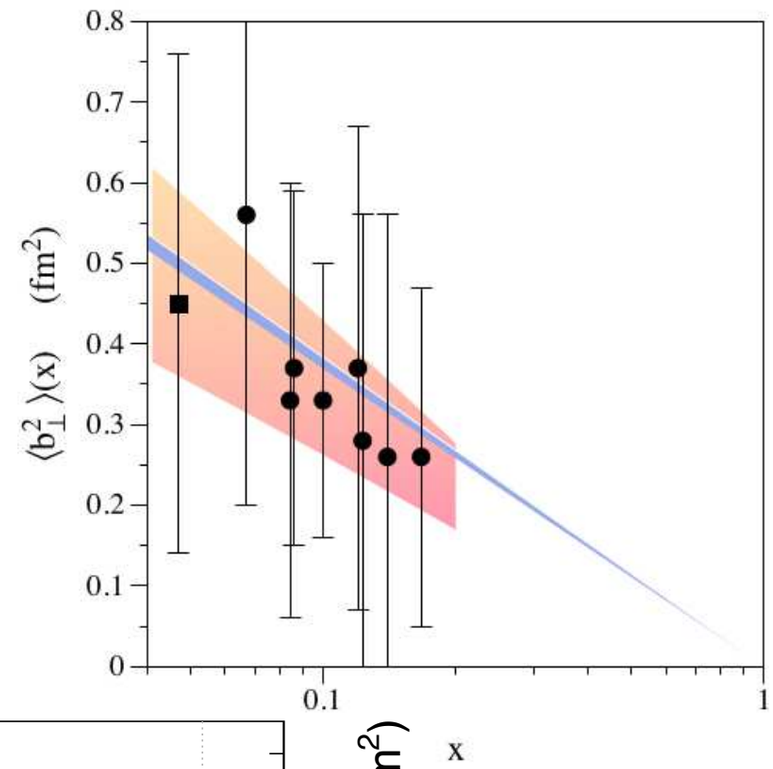
They are fitted with some ansatz and the slope at t=0 for each value of ξ is extracted

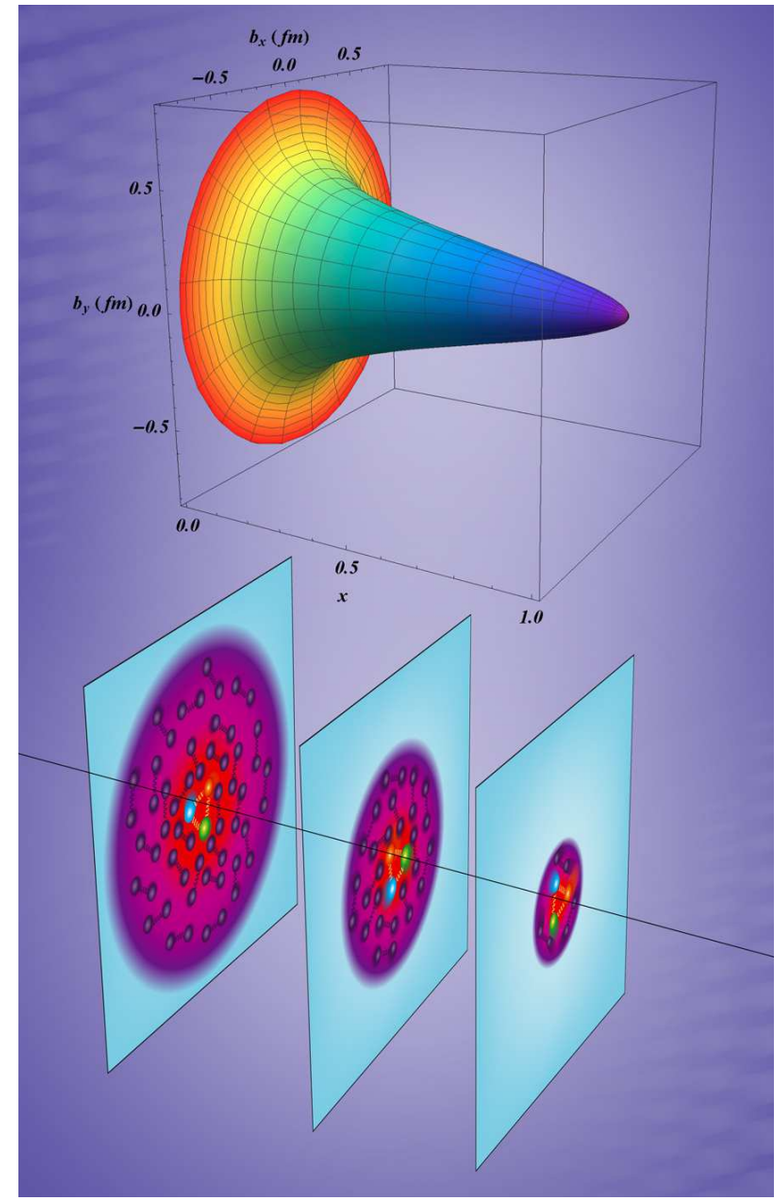
$$H_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

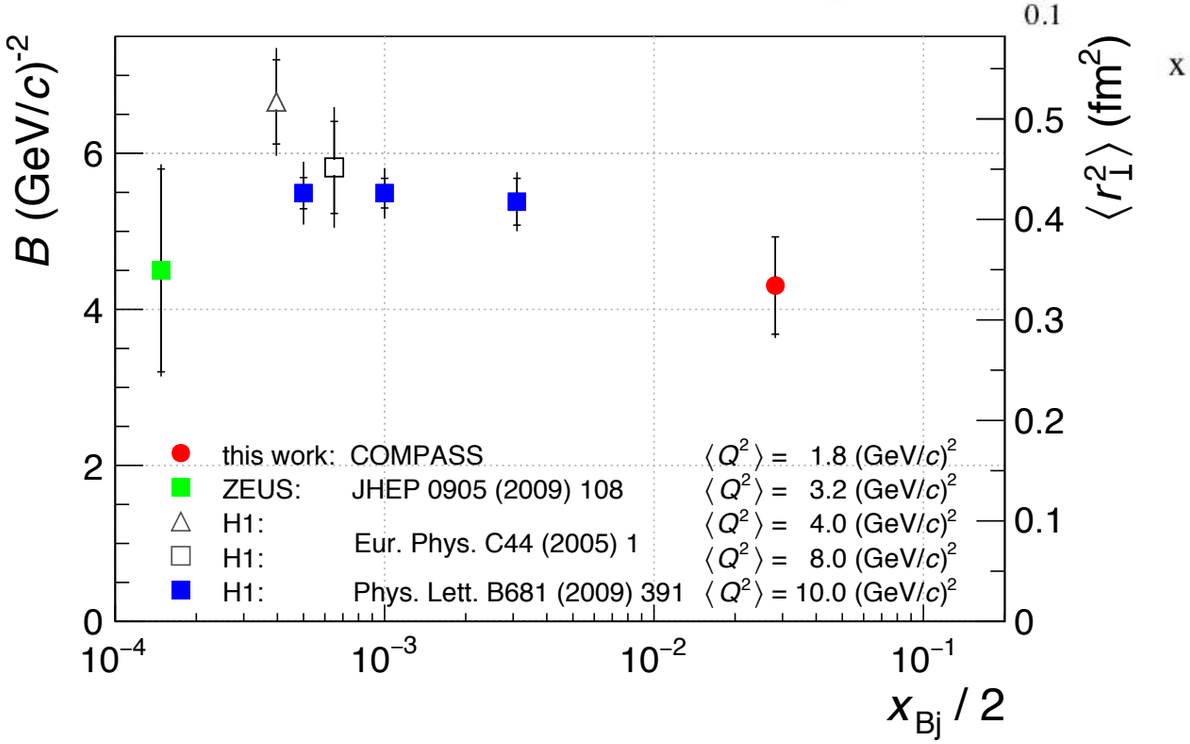
Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330

IMPACT PARAMETER DISTRIBUTIONS

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330



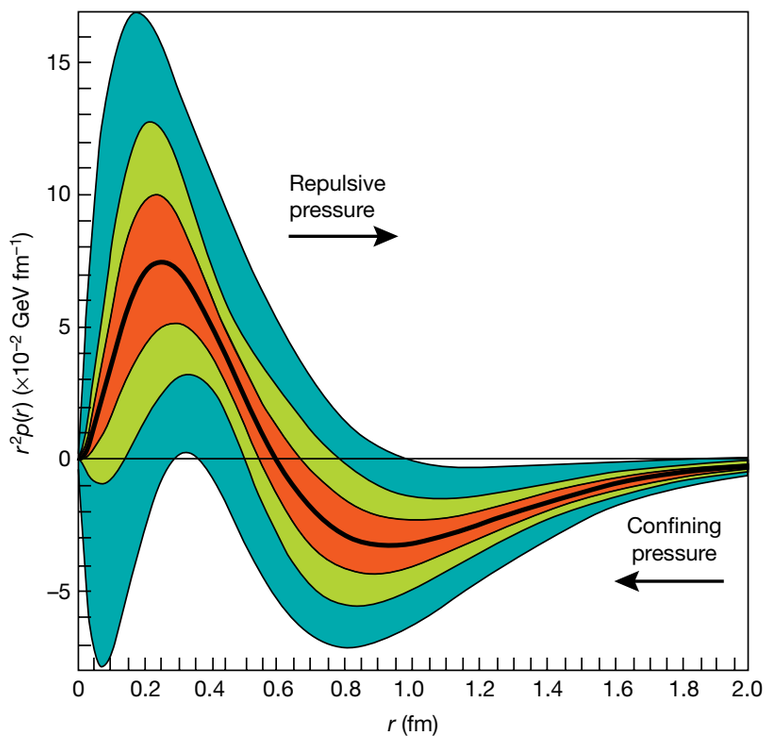




COMPASS coll., arXiv:1802.02739

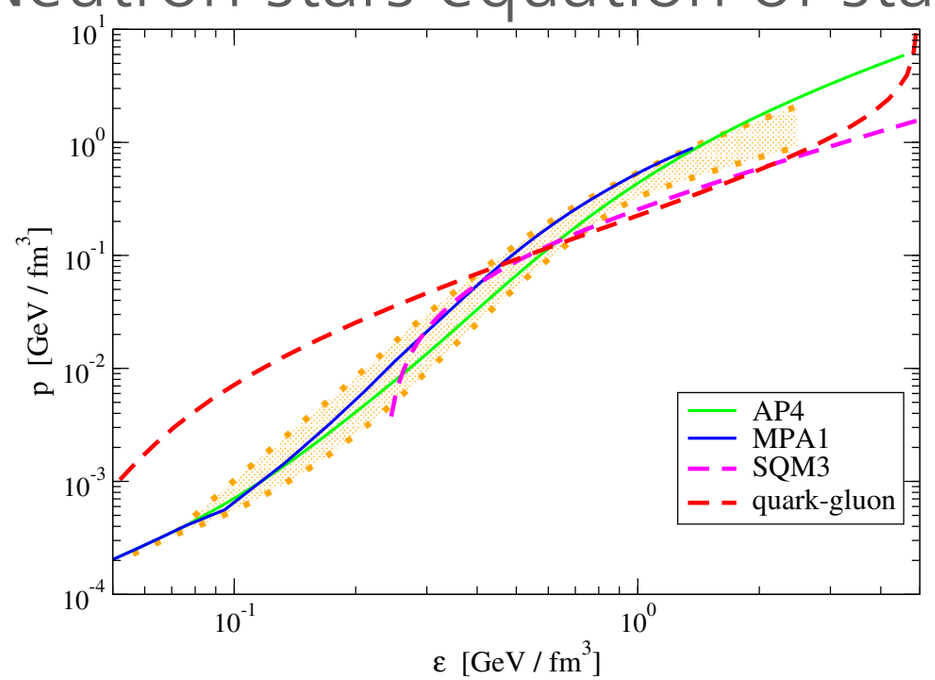
PRESSURE DISTRIBUTION IN THE PROTON

The study of the multidimensional structure of the proton can in principle allow us to access the proton energy-momentum tensor



Burkert, Elouadrhiri, Girod, Nature 577 (18)

Neutron stars equation of state

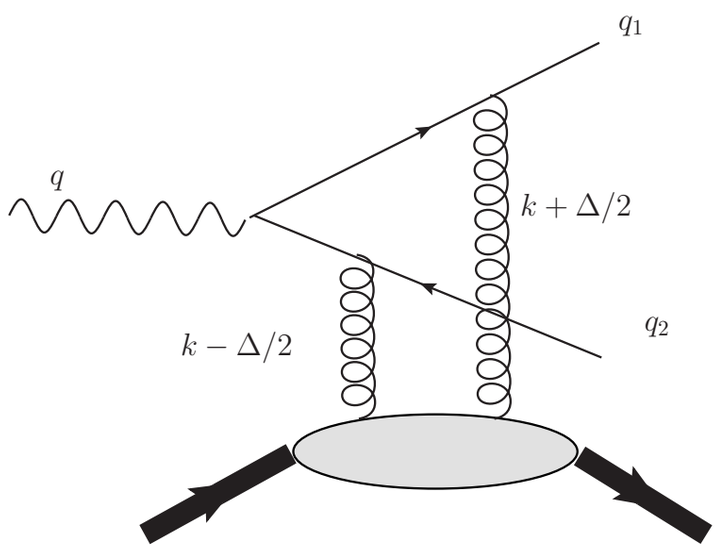


Liuti, Rajan, Yagi, arXiv:1812.01479

The knowledge of pressure in hadronic matter can in principle allow us to make predictions on the behaviour of neutron stars

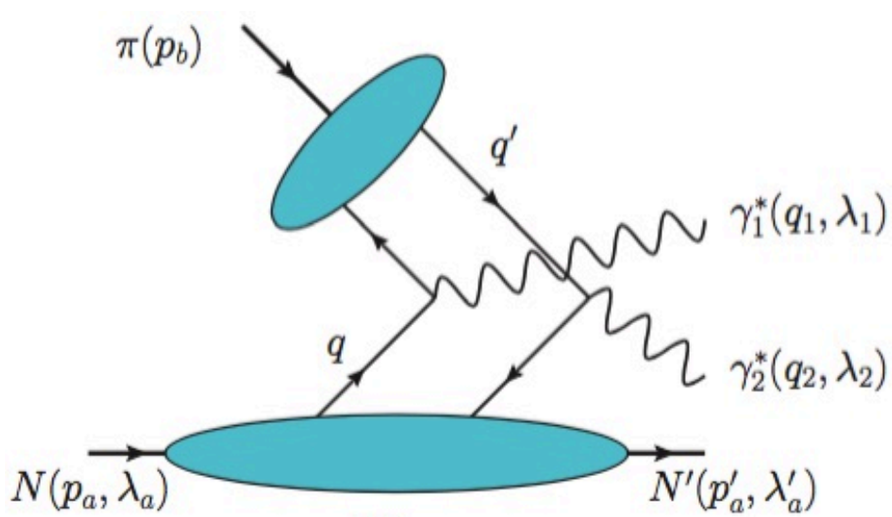
Tantalizing results. Need more solid underpinning.

WIGNER DISTRIBUTIONS



Exclusive dijet production

Hatta, Xiao, Yuan, arXiv:1601.01585
Hatta, Nakagawa, Xiao, Yuan, Zhao, arXiv:1612.02445
Ji, Yuan, Zhao, arXiv:1612.02438



Exclusive double Drell-Yan

Bhattacharya, Metz, Zhou, arXiv:1702.04387

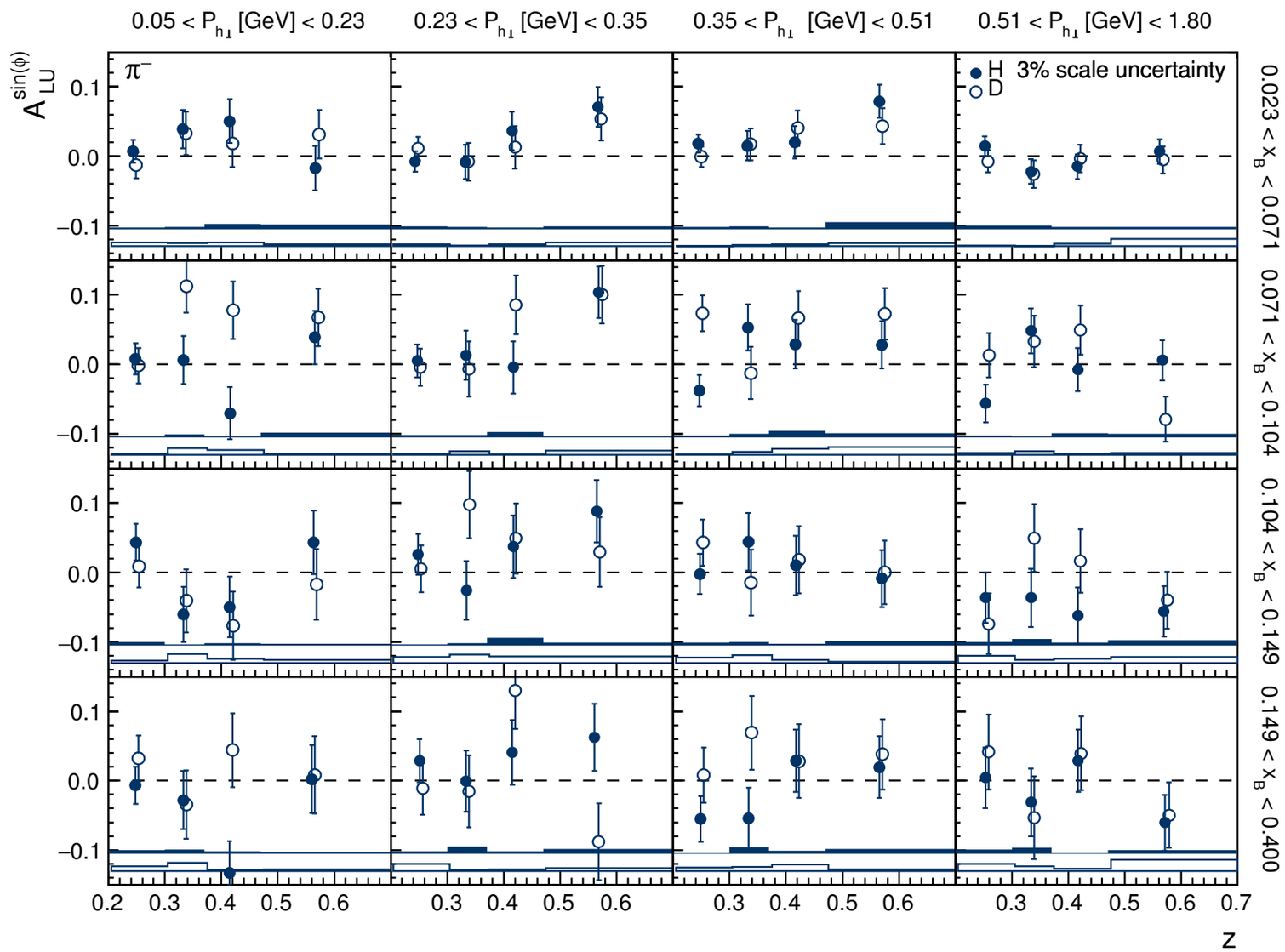
Our knowledge of GPDs keeps increasing

The study of the structure of the proton can have an impact even on astrophysics

THE FUTURE

"NEW" DATA FROM HERMES!

Multidimesional binning

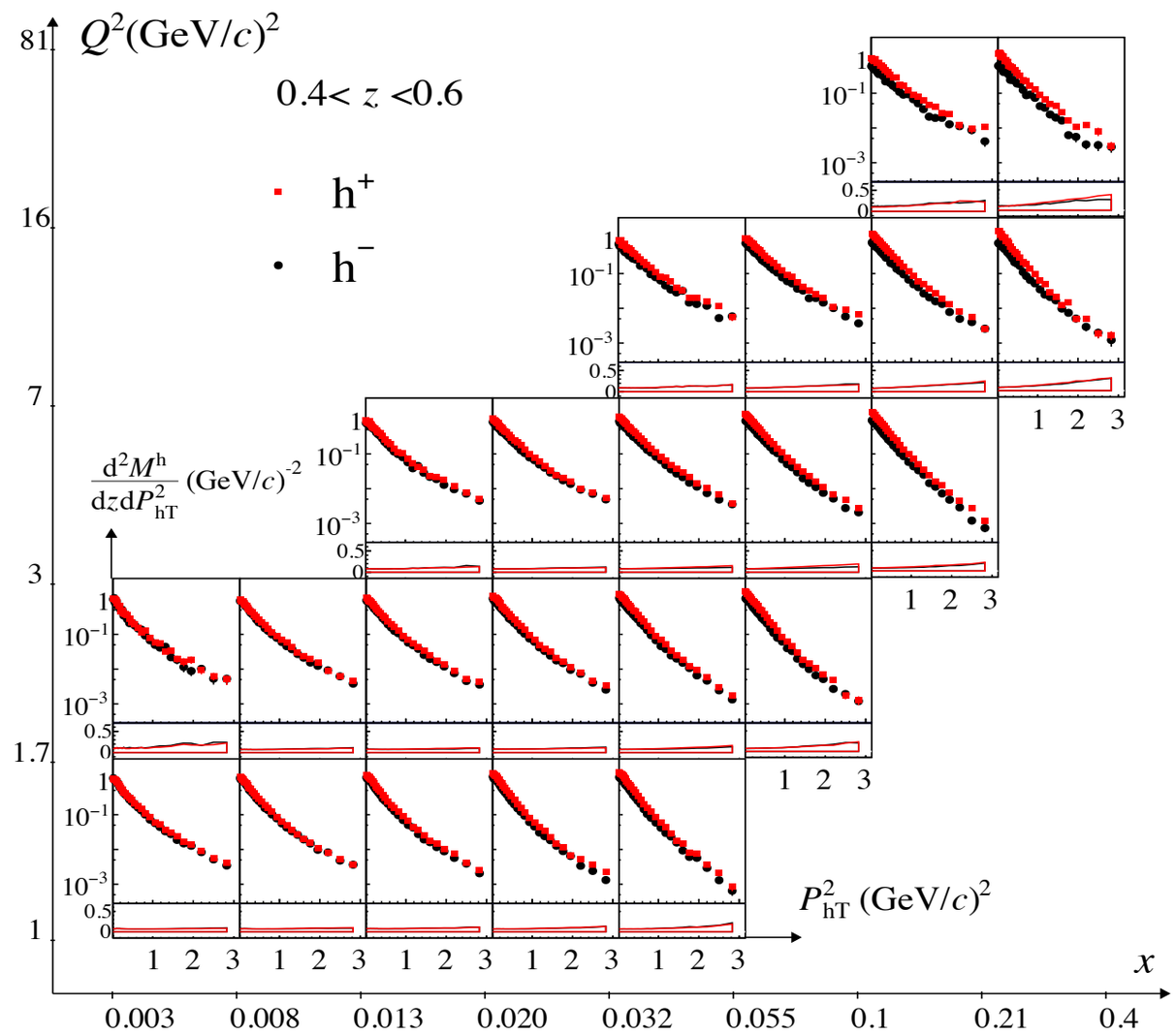


HERMES Collab., arXiv:1903.08544

Even if the experiments was closed 10 years ago, they are still producing results

NEW DATA FROM COMPASS

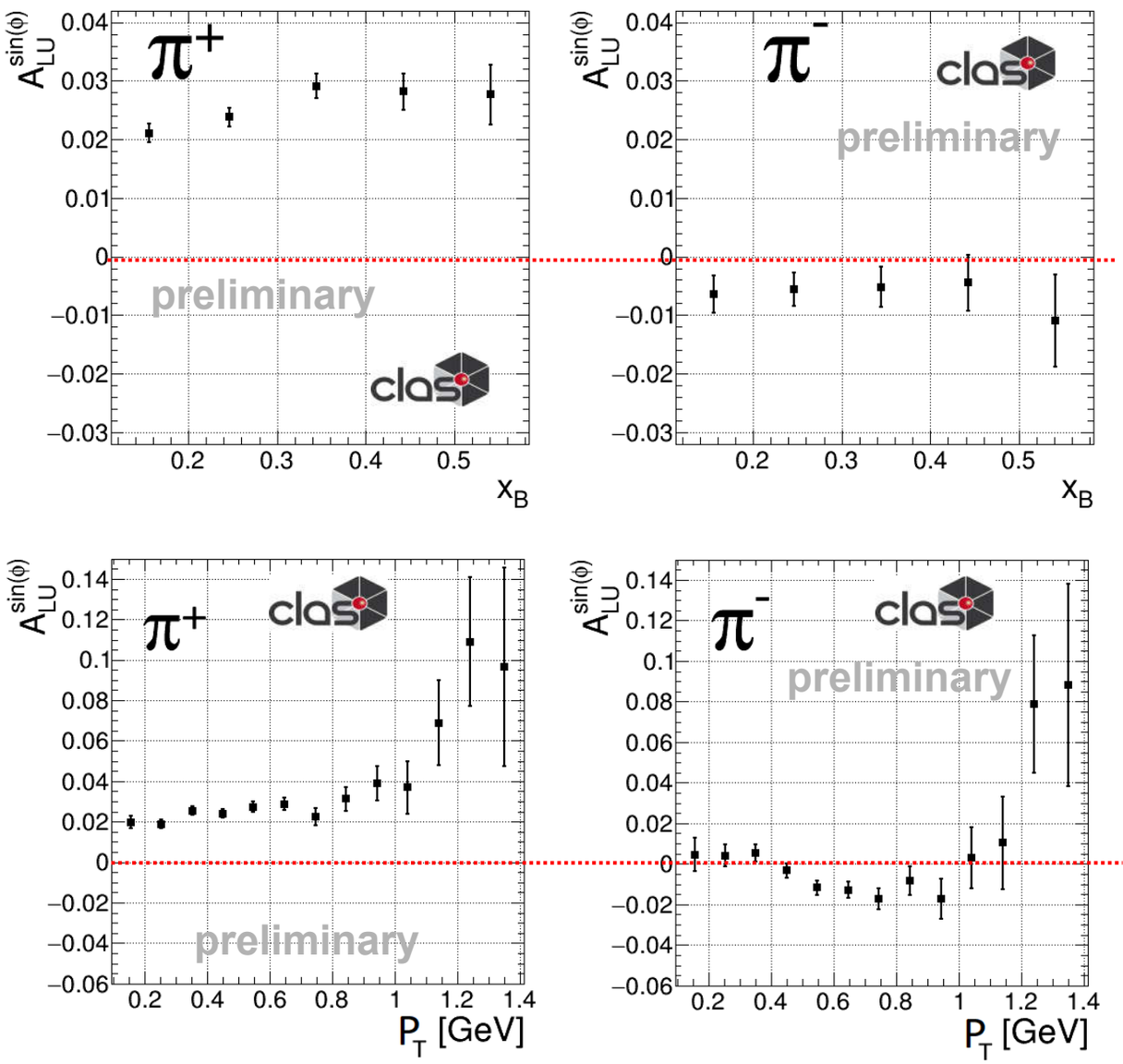
Multidimesional binning

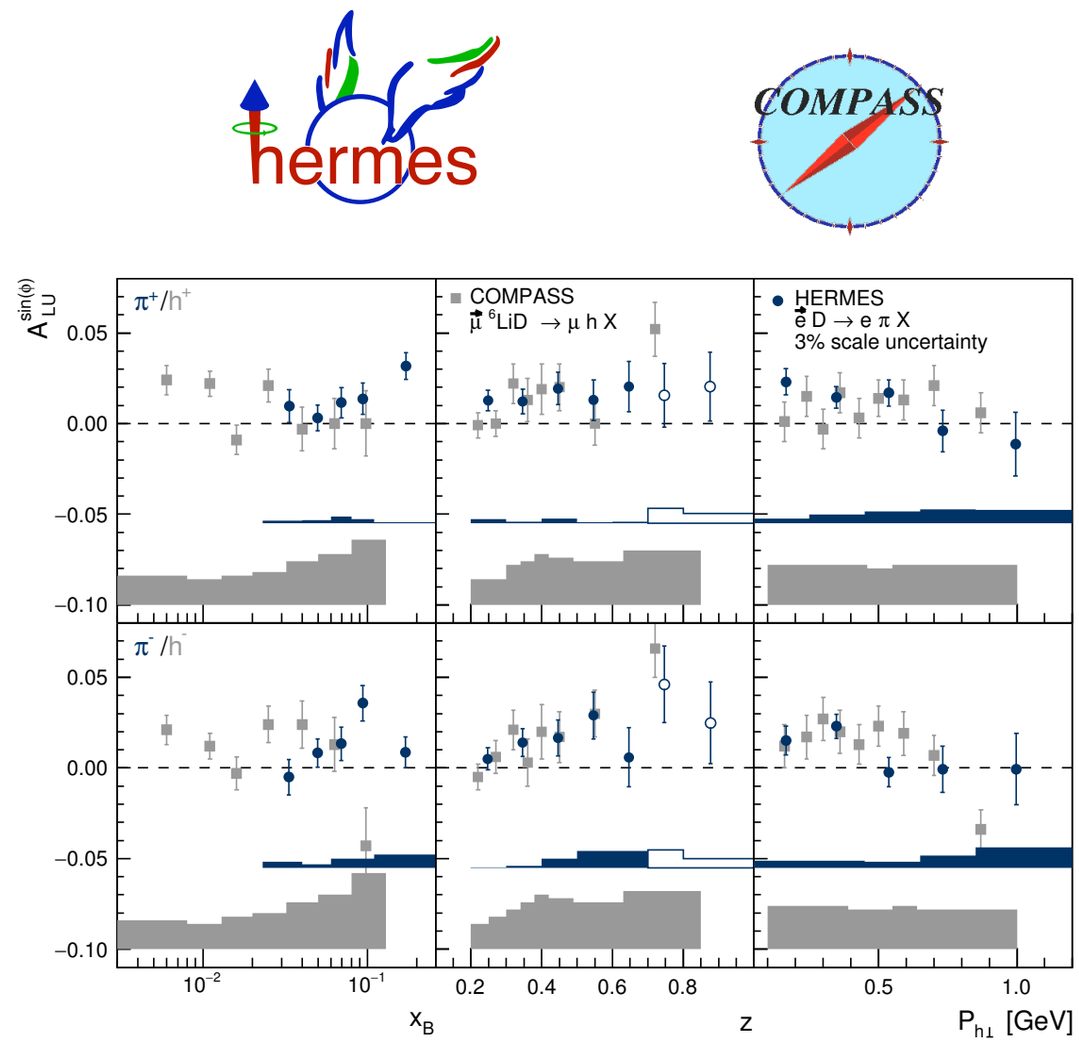


COMPASS Collab., arXiv:1709.07374

COMPASS is in "full swing" mode. The collaboration is presenting 8 contributions to the spin Working Group

FIRST JLAB PRELIMINARY DATA

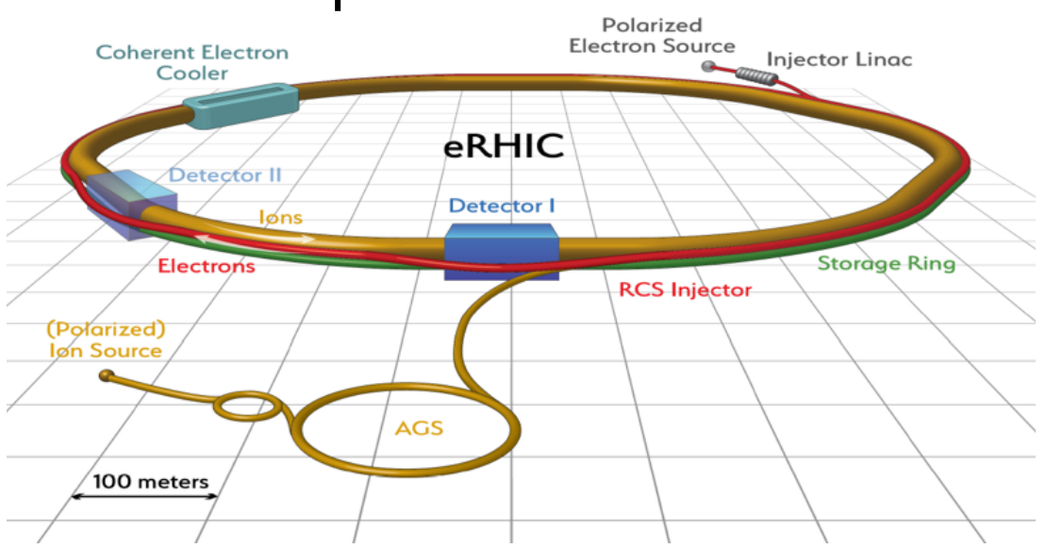




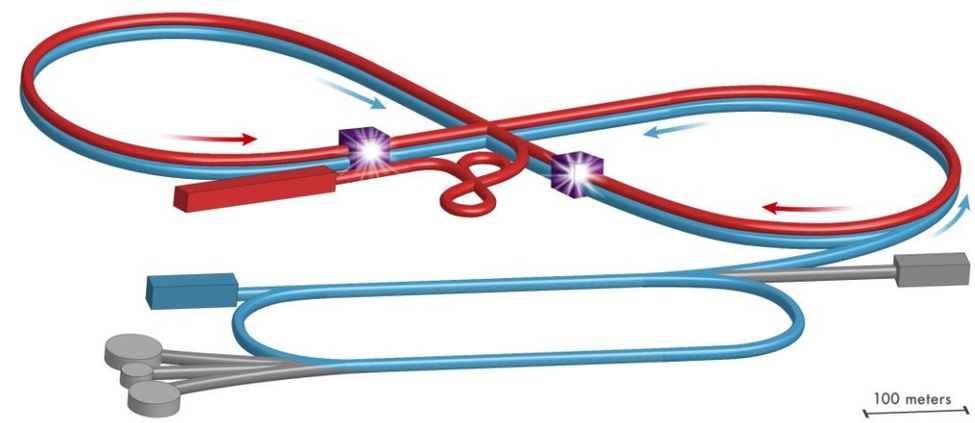
Only 2% of approved data taking!

THE ELECTRON-ION COLLIDER PROJECT

BNL concept



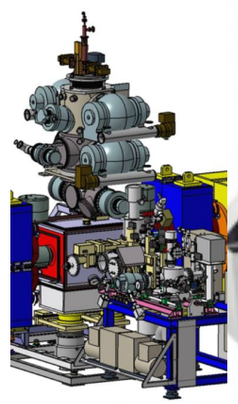
JLab concept

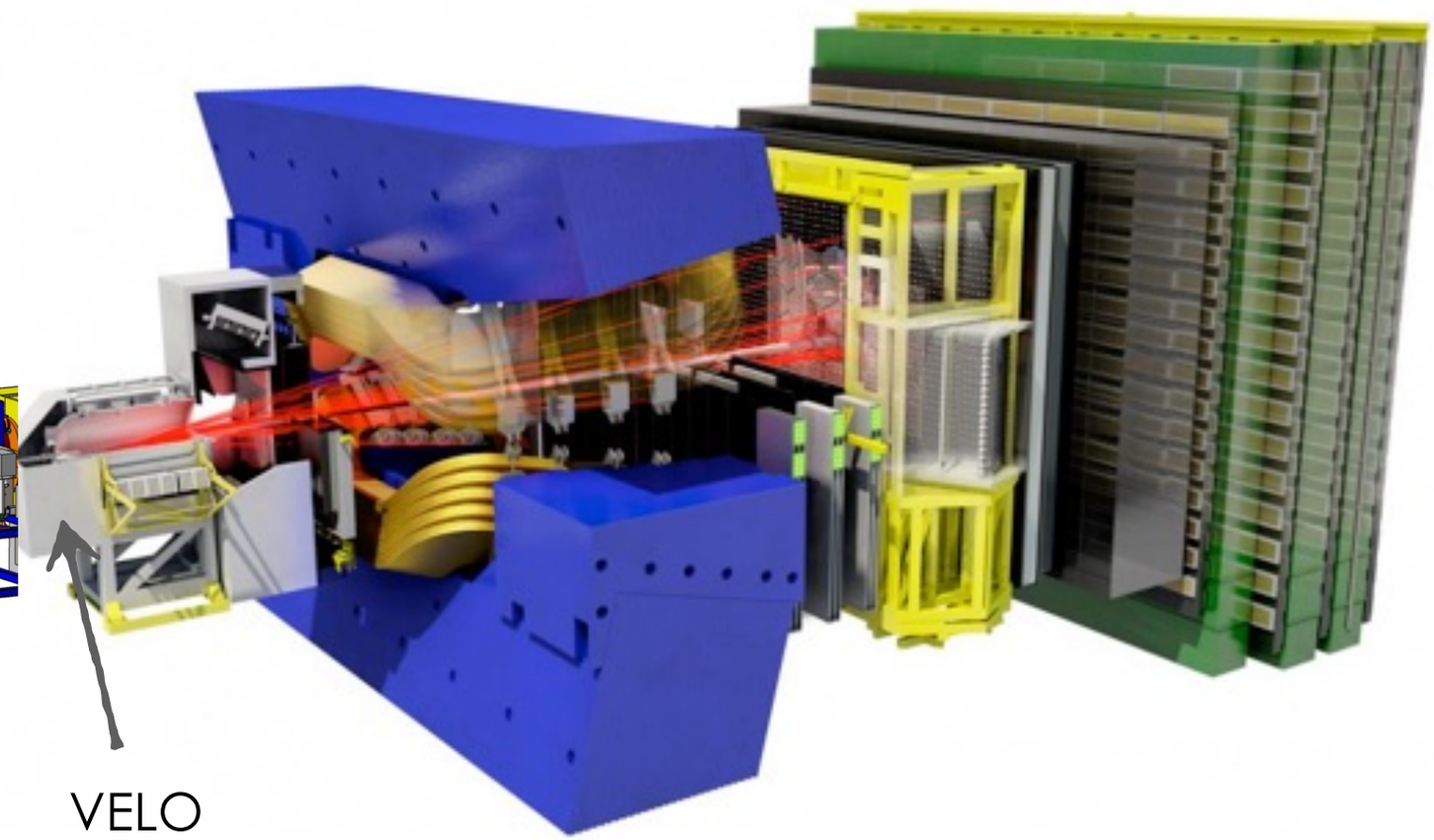


- High luminosity: (10^{34} cm^{-2} s^{-1})
- Variable CM energy: 20-100 GeV
- Highly polarized beams
- Protons and other nuclei

LHCb FIXED TARGET, INCLUDING POLARISATION

https://indico.cern.ch/event/755856/



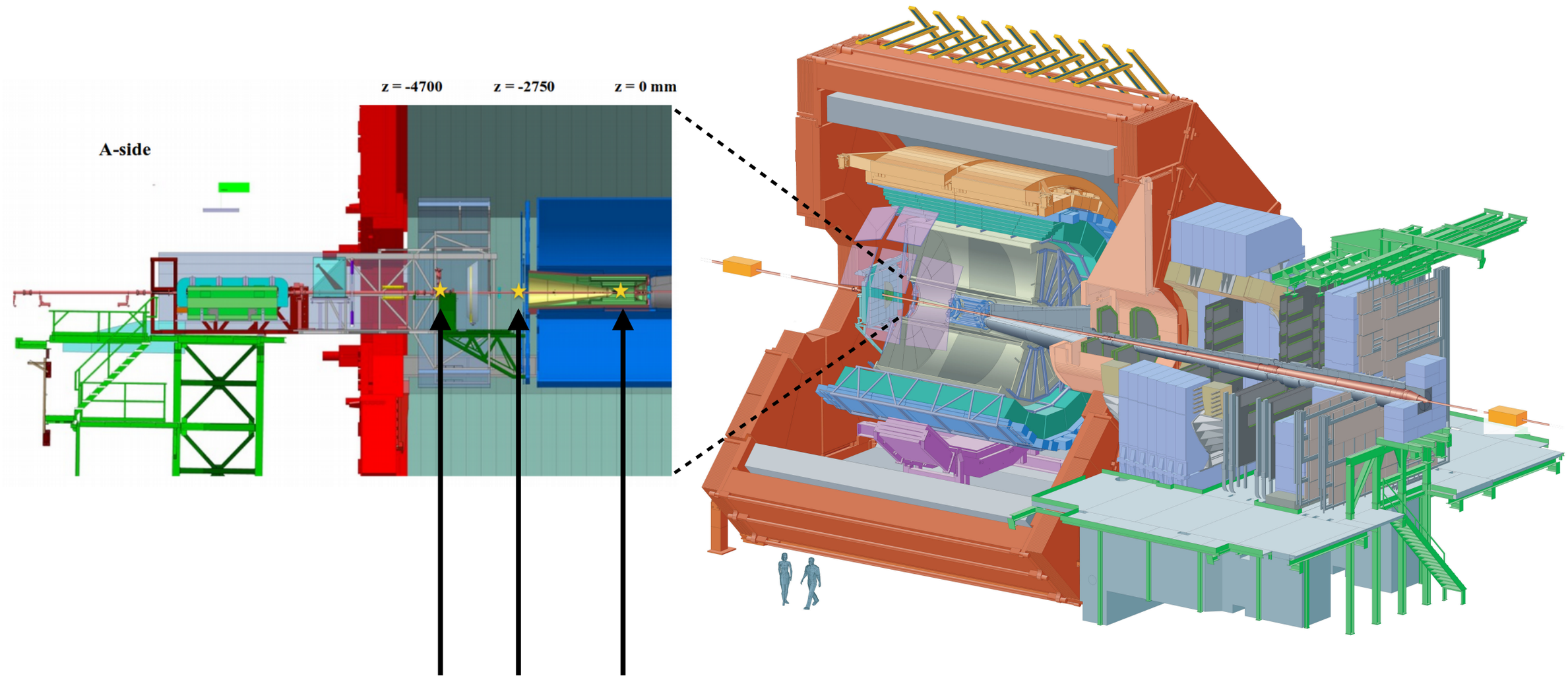


Polarised target

VELO
and SMOG2

ALICE FIXED TARGET

https://indico.cern.ch/event/755856/

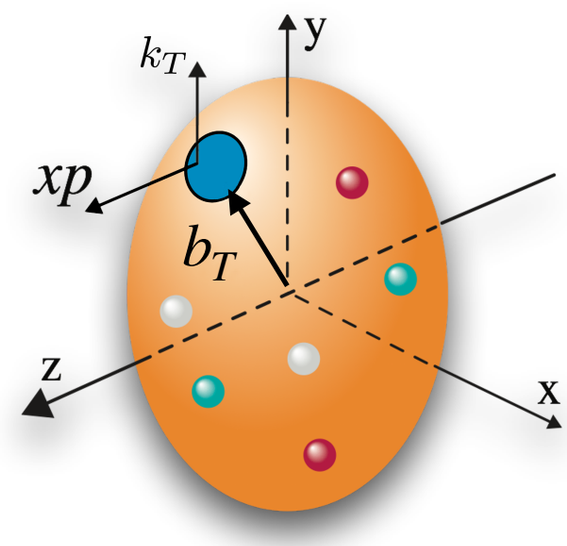


Possible fixed-target positioning

Perturbative QCD

Lattice QCD

Experiments



Beyond the Standard Model

Astrophysics

Monte Carlo generators